THE EMERGING GLOBAL WATER CRISIS: MANAGING SCARCITY AND CONFLICT BETWEEN WATER USERS

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For the first time in human history, human use and pollution of freshwater have reached a level where water scarcity will potentially limit food production, ecosystem function, and urban supply in the decades to come. The primary reason for this shortage is population growth, which has increased at a faster rate than food production for some years and will add up to 3 billion more people by the middle of the twenty-first century, mostly in poor and water-short countries. Water quality degradation has also contributed significantly to a number of problems of global concern, including human drinking water supply and species survival. As of today, some 1.1 billion planetary inhabitants do not have access to clean drinking water, and 2.6 billion do not have sanitation services. Water pollution is a leading cause of death worldwide, and transmits or supports numerous debilitating diseases to populations forced to drink contaminated water. Agriculture is by far the leading user of freshwater worldwide, accounting for almost 85% of global consumption. Because of growing demand, we will need to raise food production by nearly 50% in the next 50 years to maintain our present per capita supply, assuming that the productivity of existing farmland does not decline. Further, we will have to increase it by much more if we are also to alleviate malnutrition among the poorest members of our current population. For a variety of reasons, feasible expansion of irrigated agriculture will be able to accommodate only a portion of this increased demand, and the rest must come from an increase in the productivity of rainfed agriculture. In the absence of coordinated planning and international cooperation at an unprecedented scale, the next half century will be plagued by a host of severe water-related problems, threatening the well being of many terrestrial ecosystems and drastically impairing human health, particularly in the poorest regions of the world. The latter portion of this chapter discusses ways in which this emerging crisis may be mitigated.

I. INTRODUCTION

A century ago, the rivers of the world all ran wild and discharged the bulk of their contents into the seas. Groundwater use was limited to manual extraction from wells that only tapped the near surface, and crops were grown mostly with rainwater. Wetlands existed wherever nature intended them to be, and provided both habitat for waterfowl and a host of water regulation services. Water pollution was caused mainly by disposal of human sewage, added in small enough quantities that only the immediate zones surrounding the emissions were adversely affected. The oceans were thriving with life, and species reproduced rapidly enough to balance any losses from human consumption. A little more than 1.5 billion humans inhabited the planet, less than one quarter of today's population. And except in extremely arid zones, they had plenty of water.

The next 100 years will be quite different than the last century, as another 3 billion or so humans join the current population of 6.5 billion. Without immediate action and global cooperation, a water supply and water pollution crisis of unimaginable dimensions will confront humanity, limiting food production, drinking water access, and the survival of innumerable species on the planet.

A. Signs of the Coming Crisis

This dire forecast is based on an extrapolation of current activities and trends on the planet. First, unlike estimates of the global supply of scarce minerals or underground fuels which are surrounded by uncertainty, planetary supplies of water are relatively well characterized. There are no large groundwater deposits awaiting human detection in readily accessible locations, so that any new resources discovered will be very expensive to develop. Second, many vital human activities have become dependent on utilizing groundwater supplies that are being exhausted or contaminated. Third, much of the population growth projected for the next century will occur in areas of greatest water shortage, and there is no plan for accommodating the increases. Finally, global economic forces are luring water and land from food production into more lucrative activities, while at the same time encouraging pollution that impairs drinking water quality for a large and ever-growing segment of the population. These and other signs indicate that we are heading toward a future where billions of people are forced to live in locations where their needs for food and potable water cannot be met.

This is not the first time that modern civilization has faced an impending food crisis. In 1950, the world produced 630 million tons of grain for its population of 2.5 billion humans, a yield that was insufficient to prevent starvation in certain regions. Most notably, China suffered a massive famine at the end of the decade that killed as many as 30 million people (Smil, 1999), prompting talk that the global population might have reached or exceeded the maximum number of people who could be fed by existing resources. But the Green Revolution changed the earth's productivity dramatically through a combination of crop breeding strategies, fertilization, pest control, and irrigation (Borlaug, 2002). By 1990, grain production had risen to 1.77 billion tons to feed a population of 5.3 billion, an increase of 2.8 times the 1950 yield to provide for less than 2.1 times the number of people. This dramatic increase in productivity has had the effect of both assuaging fears of global famine and giving the world public a sense that human ingenuity would always be able to produce the technology it needed to survive and prosper.

In the nearly half century since the great Chinese famine, global agriculture has steadily produced impressive increases in crop yield. Today, irrigation, synthetic fertilizers, and pesticides are in widespread use in all but the poorest parts of the world. China and India, each with over a billion inhabitants, are both able to feed their huge populations. Yet, there is as much concern today about exceeding the planetary carrying capacity as there was in the days immediately prior to the Green Revolution. The reason for the concern is that the global population has vaulted upward to 6.5 billion in 2006, and for some time has been increasing at a rate which outpaces gains in food production. The best current population forecasts are that the world will have 7.9 billion people by 2025 and 9.2 billion by 2050. Thus, to maintain our present per capita supply we will need to raise food production by nearly 50% in the next 50 years, assuming that the productivity of existing farmland does not decline. Further, we will have to increase it by much more if we are also to alleviate malnutrition among the poorest members of our current population. Meeting future food demand will be a significantly more challenging task than the world faced prior to the Green Revolution when agricultural efficiency was low everywhere.

B. POPULATION AND FOOD PRODUCTION TRENDS

Food production and population have both been increasing steadily since the dawn of the Green Revolution, but the latter has been rising more rapidly for decades. One way to visualize the relative growth of these two dynamic variables is to look at the global grain yield (wheat, rice, and coarse grains) per person as a function of time since the Green Revolution began (Fig. 1). This index peaked in the early 1980s and has gradually declined since, reaching a low of 15% below its maximum value in 2003 before rebounding in 2004–5. At the same time, the ratio of global grain stocks to annual consumption has fallen steadily during the last decade to an all time low (Fig. 2).

The cause and significance of the declining grain yield per capita are a matter of debate. To some, it indicates that a crisis in food production is looming which threatens to make many countries that are currently self-sufficient into food importers, fighting for a declining supply of surplus (Brown, 2004). To others, the decline has been caused mainly by market forces and is not indicative of a limit to yield potential (FAO, 2003). Regardless of the explanation for the slowing of grain yield increases relative to population growth, the trend is a cause for concern if only because population growth has not ceased and significant increases in global crop yield will be necessary to avert food shortages in the future.

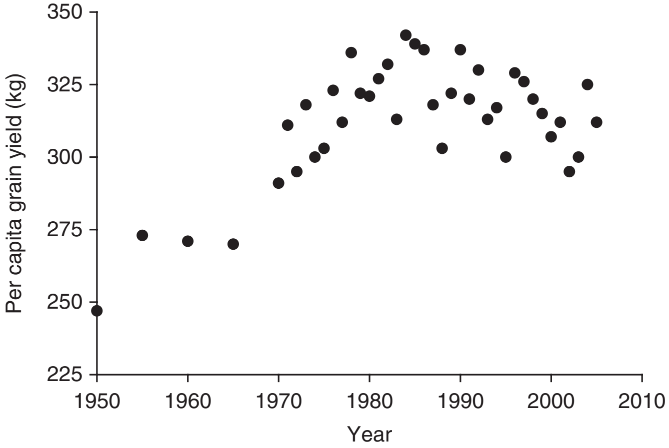

Figure 1 Total grain yield per person (data taken from FAS, 2006).

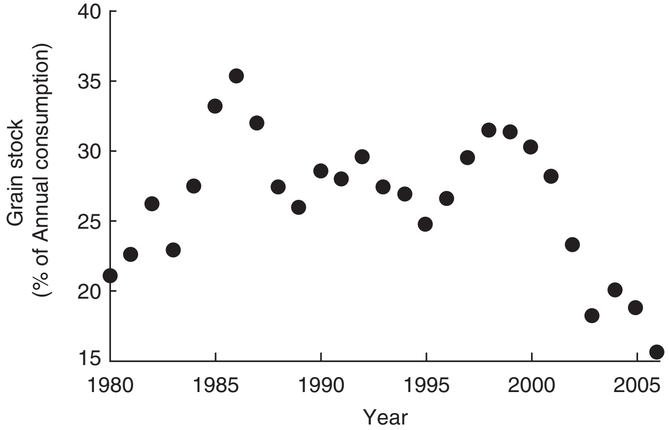

Figure 2 Ratio of grain stocks to annual consumption as a function of time (data taken from FAS, 2006).

The optimists among those who predict the future of food production have many facts to bolster their arguments. Crop yields in numerous poor countries are far below maximum attainable levels that have been reached elsewhere (FAO, 2003). Substantial additional land is available for agricultural expansion (Greenland *et al.*, 1998). Introduction of irrigation technology to areas with marginal rainfall for crops can produce substantial benefits (Postel, 1999). And genetic alteration of plant species could greatly improve the productivity of agriculture (Hoisington *et al.*, 1999).

However, the pessimists are no less able to find support for their contention that the future world will be challenged to provide the food it needs to survive and prosper. A significant part of the world's agricultural land is being managed unsustainably, and cannot continue to be farmed indefinitely (Eswaran *et al.*, 2001). Market forces in developing countries are driving the conversion of agricultural land to urban or industrial use. Loss of topsoil from water or wind erosion is decreasing the fertility of many soils. And perhaps the most compelling of all the arguments made by those looking with trepidation at the next 50 years on earth is simply that we may be running out of freshwater.

C. THE GLOBAL FRESHWATER RESOURCE

About 97.4% of the water on the planet is in the oceans, and is too saline for beneficial use without treatment. Most of the rest of the water (about 2%) is also unavailable because it is locked up in polar ice or glaciers. Humans and all other terrestrial life must subsist on the remaining 0.6%. The global freshwater (nonsaline) resource that is potentially available for human use is divided into groundwater or surface water in rivers, lakes, and reservoirs, which together total about 475 million km^3 (Shiklomanov, 1997). This is a staggering amount, but focusing on the global freshwater storage resource alone is misleading because much of the water is inaccessible. For that reason, it is more sensible to consider humanity's freshwater resource as consisting of three sources: rainfall used to grow crops, accessible groundwater, and surface water. Falkenmark and Rockstrom (2004) divide this resource into two categories which they call blue water and green water. Blue water is the liquid resource remaining after evaporation, and green water is the water originating as rainfall that subsequently returns to the atmosphere after evaporation or transpiration. Transpired rainwater is clearly a vital part of the resource for food production, and must be figured into estimates of present or future water shortages.

The blue water resource of global runoff potentially accessible to humans is difficult to estimate, and has considerable uncertainty (Postel *et al.*, 1996). A frequently quoted value is 42,700 km^3 (Shiklomanov, 1997). Global runoff is not evenly distributed over the planet's surface, so that there are some regions with excess water and others with chronic shortage. In regions with excess water, much of the volume flow of rivers and streams reaches the ocean without being used by humans, although it serves important environmental purposes. For example, 20% of average global runoff flows through the Amazon River, where it is mostly unutilized by the indigenous population (Gleick, 1998). Also, substantial flow reaches the Arctic Ocean from six major Eurasian rivers that are scarcely touched by humans

(Peterson *et al.*, 2002). In contrast, large areas of the globe receive low rainfall and are water deficient. Regions experiencing the greatest shortfall of freshwater are the Middle East, significant portions of Africa, and some parts of Europe and Southeast Asia (Postel, 1997).

D. POLLUTION AND HUMAN HEALTH

Not all of the freshwater resources are fit for human consumption. The World Health Organization estimated in 2000 (WHO/UNICEF, 2000) that 1.1 billion people on the planet lacked access to safe drinking water (Table I), and 2.6 billion did not have sanitation services. Indeed, water pollution is a leading cause of death worldwide, and transmits or supports numerous debilitating diseases to populations forced to drink contaminated water. Because of continued population growth and rapid economic development in a number of countries with little or no water quality monitoring or regulation, water pollution from industrial, municipal, or agricultural sources is growing worse in many regions, and threatens to further reduce the supply of usable water in countries experiencing scarcity.

E. CHALLENGES IN OPTIMIZING WATER USE

Determining whether a country has a sufficient water supply to serve both its present and future population is a complex matter because the relationship between population and water demand is contingent on many factors. A nation with enough wealth to import the food it needs to feed its population has a greatly reduced water demand compared to one that must grow its own nourishment. Moreover, a nation that can grow crops using only rainfall has a very different water budget than one relying on irrigation. Eating habits are also very important in determining water demand, particularly when meat is a significant portion of the diet.

Table I
Population in Millions Lacking Access to Safe Drinking Water in 2000 (Pacific Institute, 2003)

Region	Rural	Urban	Total
Africa	256	44	300
Asia	595	98	693
Latin America and Caribbean	49	29	78
Europe	23	3	26
World	926	173	1099

Because human needs for water will take precedence over all other water demands, providing the water needed to maintain ecosystem protection in the presence of conflicting water demands will pose perhaps the greatest challenge of all, given the high market value of water for industrial and municipal uses, and the obvious priority water-short countries will place on providing food and water services for their population. Substantial damage has been done to the world's ecosystems in the last century by modifying natural water courses, for example, by draining wetlands, constructing dams, excessive pumping of groundwater, or exhausting the flow of rivers. Countless other ecosystems have been stressed by water pollution originating from human activity. Optimizing water use among the agricultural, industrial, municipal, and environmental sectors cannot be achieved without consensus agreement on a clear set of priorities and a commitment to the long-term well being of the planet.

Numerous global trends are pointing to a growing water crisis that could have devastating consequences for human health, economic stability, and ecosystem protection by the middle twenty-first century, if not sooner. Averting this crisis will require international cooperation on an unprecedented scale, using a mix of technological and institutional procedures designed to utilize water more efficiently and optimize its benefits to humans and the environment.

II. THE PRESENT GLOBAL WATER SITUATION

Estimates of the annual surface water flow that is potentially available for human use vary considerably, but the figure of 12,500 $\mathrm{km}^3\ \mathrm{year}^{-1}$ used by Falkenmark and Rockstrom (2004) suffices for purposes of illustration. This volume is considerably less than the figure of 42,700 $\mathrm{km}^3\ \mathrm{year}^{-1}$ quoted for global surface water runoff, but a substantial portion of the latter is either geographically unavailable, necessary for groundwater recharge, or temporally unavailable (Postel *et al.*, 1996). Although the global freshwater supply in the aggregate is more than sufficient to meet all current and forecasted demands for consumptive use, this statement fails to represent the status of the planet's freshwater resource because there are many regions where indigenous supplies are completely inadequate to support sustainable food production and other consumptive uses.

Global water consumption by humans is increasing each year as population rises and developing countries increase their degree of urbanization and industrialization. Figure 3 shows the results of a comprehensive analysis of human water consumption for years up to 1995, with projections to 2025 (Shiklomanov, 1997).

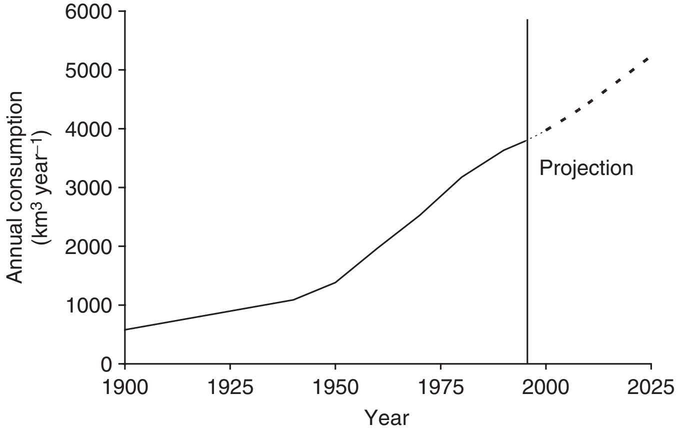

Figure 3 Global freshwater consumption in km^3 year^{-1} with projections to 2025 (Data taken from Shiklomanov, 1997).

Although the use projected for 2025 is still less than 25% of the surface water supply, humans cannot utilize all of the available surface water without destroying ecosystems that depend on water for survival. Riparian ecosystems, for example, require that a substantial fraction (e.g., 30%; Falkenmark and Rockstrom, 2004) of the annual flow volume must be maintained for adequate ecological health. This volume is not being provided in a number of riparian ecosystems today, and future demands will surely place even greater stress on the environment. Postel *et al.* (1996) estimated that about 18% of all available water in 1990 was used directly by humans, and an additional 34% is necessary for proper ecosystem function. They projected that these two needs could comprise as much as 70% of available runoff by 2025. Viewed in that light, it is easier to see that human freshwater use, even averaged on a global basis, is going to be a significant fraction of the available resource in the coming century.

A. Water Use by Sectors

In 1995, about 3800 km^3 of freshwater was withdrawn from surface water or groundwater supplies for human use (Shiklomanov, 1997). Of that amount, some 2100 km^3 was consumed, and thus removed from the supply base. Table II summarizes how that water was distributed among the four major use categories. Several facts on this table are worth noting. First, agriculture is overwhelmingly the dominant consumer of freshwater, accounting for nearly 85% of all water lost. Most of this is due to plant

Table II
Annual Global Withdrawal or Consumption of Freshwater in km^3 year^{-1} by Use Category in 1995 (Data taken from Shiklomanov, 1997)

Sector or use category	Annual withdrawal	Total withdrawal (%)	Annual consumption	Total consumption (%)
Agriculture	2504	66.1	1753	84.5
Municipal	344	9.1	50	2.4
Industry	752	19.9	83	4.0
Reservoir losses	188	4.0	188	9.1
Total	3788	100.0	2074	100.0

transpiration of irrigation water. Second, although industry and municipal withdrawals of water are significant (29% of the total), much of their withdrawal is returned to the supply base, leaving only 6.4% that is actually consumed. Finally, the second highest consumption category is due to reservoir losses from evaporation and leakage.

Quality reductions in the water returned to the freshwater supply are not reflected in the figures given in Table II. For example, the $2504 - 1753 = 751$ km^3 of water withdrawn by agriculture but not consumed includes a substantial component of agricultural drainage water that is higher in salt, nutrient, and pesticide concentration than the supply water originally withdrawn. In addition, domestic and industrial water returned to the source in developing countries is often highly polluted, and thus is not only unusable for many purposes but also degrades the remaining supplies.

B. WATER-SCARCE AND WATER-STRESSED COUNTRIES

The distribution of freshwater around the globe is highly uneven, leading to regional shortages or excesses that are not apparent from the global average figures. Moreover, the amount of water a country needs depends mostly on whether it grows or imports the food to feed its population, and how much rain it receives. There are also substantial differences in household and industrial water consumption between poor and wealthy countries. The global average water requirement for food production has been estimated as ~1200 m^3 year^{-1} per person (Rockstrom *et al.*, 1999). This is about 70 times more than the estimated 18.2 m^3 year^{-1} per person that represents average per capita household use (Falkenmark and Rockstrom, 2004). Not unexpectedly, the per capita consumption of water for nonagricultural use (domestic, service, and industry) is much higher in developed countries. The United States averages about 366 m^3 year^{-1}, Europe 232 m^3 year^{-1}, and Africa only 25 m^3 year^{-1} (Falkenmark and Rockstrom, 2004).

Classification of the degree of water security of a given country may be done in a variety of ways. The most commonly used index is the Falkenmark Stress Indicator (FSI), which classifies a country in different categories of water shortage based on per capita liquid water resource availability (PWR) (surface water flow or groundwater recharge). This index has been divided into three regions for classification purposes: (1) PWR > 1700 m^3 year^{-1}, which is regarded as the amount required for water self-sufficiency, allowing a country to grow the food it needs to feed its population, and to provide all services needed for human and ecosystem health; (2) $1000 <$ PWR < 1700 m^3 year^{-1}, which indicates water stress; and (3) PWR < 1000 m^3 year^{-1}, which denotes chronic water scarcity. A PWR of 500 m^3 year^{-1} or less is considered to be a water barrier, below which a country depending on irrigation cannot avoid salinization problems and progressive loss of agricultural land. As indicated previously, the figure of 1700 m^3 year^{-1} is comprised largely of the 1200 m^3 year^{-1} per person required to produce food. Thus, the stress index primarily indicates whether a country relying on irrigation has sufficient water to grow the food it needs to feed its own population.

Although this index is arbitrary, it does allow an objective assessment of regional water availability. Table III summarizes the number of countries experiencing water stress or scarcity in 1995 according to this index. Of the 18 water-scarce countries, 9 are in the Middle East, and 6 in Africa, primarily in the extreme north.

The FSI is only one of several different ways of representing water scarcity, and at best provides a qualitative measure of a country's present or future degree of food and water security. As an alternative, Raskin *et al.* (1997) defined water scarcity in terms of the total volume of water withdrawn annually as a percentage of a country's annual water resources. This study, sponsored by the United Nations Commission on Sustainable Development, classified a country as water scarce if its annual withdrawals exceeded 40% of its total resource. Seckler *et al.* (1998) used this index together with

Table III
Population and Numbers of Countries Experiencing Water Stress or Scarcity in 1995 According to FSI (Data adapted from Population Reports, 1998)

Category	Annual water resources (m^3 year^{-1} per person)	Countries	Population (millions)
Water scarce	PWR < 1000	18 (12)[a]	166 (65)
Water stressed	$1000 <$ PWR < 1700	11	294
Water scarce or stressed	PWR < 1700	29	460

[a] Number in parentheses indicates countries below water barrier of PWR < 500 m^3 year^{-1} per person.

an estimate of the projected percentage increase in withdrawals between 1995 and 2025 to place countries in five different groups of water availability. Group 1, with both indices above 50%, was deemed the most problematic. Although the Falkenmark, Raskin, and Seckler water stress indices have some common elements, they do not produce the same classification when applied to the countries of the world.

C. Drinking Water, Sanitation, and Waterborne Disease

There are surprisingly few sources of pristine water remaining in the modern world. Even rainfall can contain substantial amounts of chemicals arising from air pollution or agricultural emissions. Rivers, streams, and lakes become contaminated from a variety of industrial, agricultural, or municipal sources, as well as from individual septic tanks or other household waste disposal practices. The nature of the pollution varies with the level of development of the region, and depends as well on whether the host country has waste control policies and cleanup procedures.

In modern wealthy countries, water sources are monitored and either treated or isolated from human contact if harmful levels of pollution are present. These societies regard safe drinking water and adequate sanitation as basic rights granted to all their citizens. Yet for a significant part of the world these services are woefully inadequate. The World Health Organization estimated that ~1.1 billion people lacked access to clean drinking water in 2002, and 2.6 billion did not have sanitation services. The problem is particularly bad in rural parts of Africa and Asia, where the majority of the citizens have no sanitation or freshwater access. Table IV shows the percentage of the population with drinking water and sanitation services in various regions of the world. These numbers show clearly that the poorer regions of the world lag far behind industrialized nations in water supply and sanitation access.

Table IV
Percentage Water and Sanitation Coverage by Region (Data taken from WHO/UNICEF, 2000)

Region	Water supply	Sanitation
Africa	62	60
Asia	81	48
Latin America and Caribbean	85	78
Oceania	88	93
Europe	96	92
North America	100	100
World	82	60

The 1.1 billion poor people in the world forced to drink contaminated water in order to survive are subjected to a host of debilitating and even fatal diseases that are virtually unknown in countries with safe drinking water and adequate sanitation services. The most widespread of the waterborne diseases are those arising from human or animal waste contamination. The World Health Organization reported that, of the 51 million deaths worldwide in 1993, about one-third (16.4 million) were caused by infectious and parasitic diseases. In developing countries these totals are even higher, with infectious and parasitic diseases accounting for 44% of all deaths and 71% of deaths in children (World Development Report, 1993). There is insufficient data to determine how much of global infectious disease is waterborne, although estimates of up to 80% have been given (Clarke, 1993).

The United Nations and the World Health Organization were sufficiently concerned about the water problems of poor nations that they designated the 1980s as the International Drinking Water Supply and Sanitation Decade, whose stated goal was to "Provide every person with access to water of safe quality and adequate quantity, along with basic sanitary facilities, by 1990." Although the goal was not reached, the UN/WHO action focused attention on the problem and greatly increased funding to address global deficiencies. As a result, rural water supply increased by 240% and sanitation access grew by 150% in rural areas between 1980 and 1990. Although urban water supply and sanitation also increased by 150% as a result of the effort, there was a net decrease during the decade in percentage access because of the large rise in urban population. Service provision efforts have continued to increase globally in the decades since, although some of the poorest countries have not been able to increase water supply and sanitation services as fast as population has grown. The percentage of the world population with access to water supply increased from 76% to 82% between 1990 and 2000, although the absolute number of people without service remained constant at about 1.1 billion. At the same time, the percentage with access to sanitation increased from 55% to 60%, but again the numbers without services changed little and remained at about 2.4 billion.

The United Nations created the Millennium Development Goals, which were adopted in 2000 by all the world's governments as a blueprint for building a better world in the twenty-first century. One target of the environmental sustainability goal was a plan to halve by 2015 the proportion of people without sustainable access to safe drinking water and basic sanitation. The assessment of the 2006 Progress Report was that the world was unlikely to reach this target in the designated time frame (UN, 2006).

The major source of pollutants in developing countries is by direct disposal of domestic and industrial wastewater into rivers, lakes, or on land. *Emerging Asia*, published by the Asia Development Bank in 1997, identified water pollution as the most serious environmental problem facing the continent

(ADB, 1997). The majority of the world's poor people reside within Asia, and over half of the total global population. Although significant efforts were made across the continent to improve both drinking water quality and access to sanitation services during the 1980s, population growth during the same time period erased much of the progress. As of 1990, some 850 million people in Asia had no access to fresh drinking water, and 2.1 billion had no basic sanitation facilities.

In Asia and the Pacific, fecal pollution is one of the most serious problems, affecting both surface water and groundwater and causing a host of waterborne diseases such as cholera, typhoid, and hepatitis. Currently, over 80% of river lengths in the Hai and Huai basins in China are classified as very highly polluted and cannot meet any designated beneficial uses. Estimates of the increase in water pollution loads in high-growth areas of Asia over the next few decades are as high as 16 times for suspended solids, 17 times for total dissolved solids, and 18 times for biological pollution loading (UNIDO, 1996).

Parasites in water or insects breeding in water cause a host of illnesses, the most serious of which are fatal. Table V lists the most serious of these water diseases, their morbidity, and the deaths they cause. These diseases kill over 5 million people per year, and incapacitate even more. In addition, other diseases that are not generally fatal can cause a variety of incapacitating injuries. For example, onchocerciasis and trachoma are responsible for over 6 million cases of blindness or equally severe complications.

Diarrhea is caused by a number of different bacterial, viral, and parasitic organisms present in contaminated water, and is a major cause of death for children who do not have access to clean water. It has been estimated that diarrhea causes 4% of all deaths and 5% of disability (WHO/UNICEF, 2000).

Malaria is caused by four species of *Plasmodium* parasites. It does not infect humans through water contact, but rather is transmitted by mosquitoes which breed in stagnant water. The disease is among the five leading causes of death in children under 5 years of age in Africa. In many regions

Table V
Estimated Morbidity and Mortality for Various Water-Related Diseases (Data from Gleick, 2002 and WHO, 2004)

Disease	Annual cases (millions)	Annual deaths (thousands)
Diarrhea	1000	3300
Malaria	400	1500
Schistosomiasis	200	20
Trypanosomiasis	0.27	130
Intestinal helminths	1500	100
Dengue fever	1750	20
Onchocerciasis	18	40

where malaria is present, the natural habitat is wet enough to provide the breeding ground for mosquitoes. However, the development of irrigation systems, dams, and reservoirs in regions lacking a natural mosquito habitat has caused the disease to spread. In other regions, for example, the Central Asian republics, malaria has returned because of the deterioration of water management facilities.

Schistosomiasis is an infection caused by three different species of flatworm that develop in freshwater snails. It infects humans who contact contaminated water by ingestion of the flatworms through the skin. At least 600 million people are at risk of infection and 200 million currently have schistosomiasis, about 80% of which are in sub-Saharan Africa. Of those infected, some 20 million have a severe and potentially fatal form of the disease. Water resource schemes for power generation and irrigation have resulted in a tremendous increase in the transmission and outbreaks of schistosomiasis in several African countries. In northern Senegal, an area without intestinal schistosomiasis before the building of the Diama dam in 1986, virtually the entire population had become infected by 1994.

Trypanosomiasis, known as sleeping sickness, is an insect vector-borne parasitic disease caused by protozoa transmitted to humans by tsetse flies, which breed along rivers, streams, and lakes. The disease occurs only in sub-Saharan Africa, in regions where tsetse flies are endemic. It currently threatens over 60 million people in 36 countries of sub-Saharan Africa. In certain provinces of Angola, the Democratic Republic of Congo, and southern Sudan, the prevalence of trypanosomiasis is between 20% and 50% of the population, making it the first or second leading cause of death in those regions.

Intestinal helminths are parasitic worms that cause intestinal infections. It is estimated that 133 million people suffer serious complications from these parasites, such as massive dysentery, anemia, or brain damage. Ascariasis, caused by the Ascarias worm, is one of the most common human parasitic infections. Up to 10% of the population of the developing world is infected with intestinal worms—mainly by Ascaris. Worldwide, severe Ascaris infections cause ~60,000 deaths per year, mostly children. Infection occurs with greatest frequency in tropical and subtropical regions, and in any areas with inadequate sanitation.

Dengue fever is a mosquito-borne infection causing a severe, flu-like illness that affects infants, young children, and adults but rarely causes death. Dengue hemorrhagic fever (DHF) is a potentially lethal complication and is today a leading cause of childhood death in several Asian countries. It is characterized by high fever, hemorrhage, liver enlargement, and circulatory failure in the most severe cases. Dengue has spread dramatically through the world in recent decades, and is considered a major health threat today. Globally there are an estimated 50–100 million cases of dengue fever and 500,000 cases of DHF each year. The disease is now found in more than

100 countries in Africa, South and Central America, the Eastern Mediterranean, South and Southeast Asia, and the Western Pacific.

A substantial fraction of the world's population is at risk from water-related diseases, and the regions where the risk is greatest also are among the most rapidly growing in population. It is likely that most of the ~2 billion people added to the world due to growth in population between 2000 and 2025 will be at risk for the diseases in Table V unless significant improvements are made in global sanitation and drinking water quality.

D. CHEMICAL CONTAMINATION IN WATER

Although the most advanced of the industrialized countries have largely controlled biological contamination of water, many of them have seriously polluted their surface water and groundwater supplies with agricultural, municipal, or industrial releases of toxic chemicals. Even in wealthy countries committed to remediation, cleanup of badly contaminated sites has been extremely time consuming and expensive. In 1994, the Congressional Budget Office estimated that it could take as much as US$75 billion to clean up the remaining 4500 non-Federal sites on the Superfund list. Similarly, the overall extent of the financial public and private environmental clean up liability risk in Germany is thought to be between 200 and 500 billion euros, mostly due to contamination in the former East Germany (Freshfields, 2003). Indeed, the evidence shows that it is almost always cheaper to prevent pollution than to remediate it once it has been released to the environment.

In contrast to pathogenic contamination, chemical pollution tends to be localized and reflective of the land use around it. Agricultural nutrients and pesticides seep to groundwater below cropped fields or concentrated feedlots, or accumulate in surface waters receiving agricultural runoff from irrigated fields. Industrial contamination occurs from leaks, accidents, or deliberate dumping, and depending on the industrial processes can contain a host of persistent toxic metals or organic compounds. Municipal waste might include untreated sewage in a developing country or toxic stormwater runoff in a developed nation. Chemical contamination is difficult to monitor in the subsurface and expensive to analyze, so that much of it is uncharacterized. In the following sections, the major chemical pollutants found in groundwater and surface water will be briefly discussed.

1. Agricultural Nutrients

Agricultural nutrients can cause significant changes in aquatic systems. Eutrophication is the term used to describe the process through which surface waters are enriched with nutrients. There are natural eutrophication processes which cause lakes and streams to evolve ecologically. There are also simpler human-induced eutrophication processes which are driven by the residues of fertilizers and other nutrient-rich materials that trigger artificial and sometimes unstable changes in aquatic ecosystems. Phosphates and nitrates are often the limiting factors in the growth of algae. Addition of the limiting chemicals can trigger significant algal blooms which are followed by a die-off and consumption of algal biomass by bacteria. This latter process can consume oxygen to levels that are toxic to fish and other aquatic organisms. Eutrophication can cause a number of undesirable effects, including: increase in production and biomass of phytoplankton and algae, shift in habitat characteristics, replacement of desirable fish by less desirable species, production of toxins by certain algae, lowering of oxygen levels by microbial respiration, and loss of functionality of the water resource (Ongley, 1996).

The principal agricultural nutrients with potentially harmful environmental consequences are nitrogen and phosphorus. Both are added in large quantities in modern fertilized agriculture, and tend to be more of a problem in developed countries with farmland under intense cultivation. Phosphorus binds tightly to soil particles, preventing it from moving deep into the soil with drainage water. Thus, it is seldom seen in groundwater. However, it is readily transported with sediment during lateral runoff, allowing it to reach streams and lakes where it can trigger an explosive growth of algae. Phosphorus does not reach high concentration levels in water, and there is no health risk associated with exposure to phosphorus in the natural environment.

Nitrogen undergoes a number of reactions in soil, and under normal conditions of adequate oxygen culminates in formation of the stable nitrate ion, which is very soluble, does not bind to stationary soil particles, and is extremely mobile in soil. If not taken up by plants, nitrates can seep below the root zone to groundwater, and move laterally to surface water with runoff. In surface water, nitrogen contributes to eutrophication of receiving bodies, and can alter the aquatic ecology through weed proliferation and algae growth.

Water containing high concentrations of nitrate can have adverse health effects. Infants under 6 months of age are most sensitive to elevated levels of nitrates in drinking water. A baby fed water high in nitrates may develop a condition called methemeglobinemia, in which the blood is unable to properly carry oxygen. The condition can be fatal, if oxygen deprivation is severe and lengthy enough. For this reason, the public health limit for nitrate in drinking water has been set at 10 mg liter^{-1} NO_3-N (45 mg liter^{-1} NO_3) in the United States and slightly higher (50 mg liter^{-1} NO_3) in Europe.

Deaths from methemeglobinemia are extremely rare in the United States and Western Europe, and those that have occurred were generally in rural areas where drinking wells had been contaminated to high levels of nitrate by septic tanks or other sources of concentrated N emissions. Under high-risk conditions, such as intensely fertilized agricultural fields containing well-drained soil above shallow groundwater, groundwater concentrations of nitrate can rise above the public health limit. Nolan *et al.* (2002) reported that 26% of the wells sampled in high-risk areas of the Midwest and western United States had concentrations above 10 mg liter^{-1}. For the period 1992–1996, over 65% of the rivers in the European Union had average annual nitrate concentrations exceeding 1 mg liter^{-1}, and 15% had concentrations over 7.5 mg liter^{-1}. The highest levels were found in Northwest Europe, where agriculture is intensive. A limited number of studies have suggested other health effects linked to nitrates, including spontaneous abortions (Centers for Disease Control, 1996), bladder cancer (Weyer *et al.*, 2001), and non-Hodgkin's lymphoma (Law *et al.*, 1999).

2. Agricultural Pesticides

The global use of chemical pesticides has undergone three stages of evolution. Until the early 1900s, inorganic toxins such as arsenic, copper, and lead were used around the world to kill a variety of pests. However, these chemicals were toxic to all organisms they contacted, and persistent in the environment. They were eventually restricted from use as pesticides.

The second stage of pesticide use began in the 1940s when synthetic organic compounds, consisting of either chlorinated hydrocarbons, carbamates, or organophosphates, were introduced for pest control. The chlorinated hydrocarbons, such as DDT, dieldren, and lindane, are nerve toxins that act on any organism with a central nervous system. They are persistent and bioaccumulate readily in the environment. The organophosphates and carbamates are less persistent, but much more toxic to humans. They also are significantly more expensive to use than the chlorinated hydrocarbons.

The most recent stage of pesticide management is the use of natural toxins in connection with a suite of procedures known as integrated pest management. Natural biocides, such as the bacterial toxin *bacillus thuringiensis*, are easily degraded into nontoxic forms. They are also much narrower in their toxicity and attack a specific target organism. Modern pest management techniques, when widely adopted, could have substantial beneficial impacts on water quality.

The Western world has begun making the transition into the third stage of pesticide use. However, developing countries still use large quantities of toxic and persistent chemicals because they are significantly less expensive to employ. As a result, pesticides have become a major health threat in the developing world, largely due to handling and exposure during application. An estimated 3 million reported cases of pesticide poisoning occur annually, resulting in 220,000 deaths (WHO, 1990). About 99% of these occur in the developing world, despite the fact that developing countries account for only 20% of global pesticide use.

The extent of pesticide contamination of surface water or groundwaters around the globe is largely unknown. It is extremely expensive and laborious to measure pesticide concentrations in soil or water, and only a few comprehensive surveys have been conducted. In the United States, the US EPA's National Pesticide Survey found that 10.4% of community wells and 4.2% of rural wells contained detectable levels of one or more pesticides (US EPA, 1992). More than 68,000 groundwater wells in 45 states were sampled in this survey, and pesticides were detected in nearly 25% of the wells and in 42 states. Analysis was carried out for a total of 605 pesticides and related compounds, of which 265 were detected at least once. Of the pesticides detected, 28 are no longer in use in the United States, and regulatory restrictions have been placed on 54. In a study of groundwater wells in agricultural southwestern Ontario (Canada), 35% of the wells tested positive for pesticides on at least one occasion (Lampman, 1995).

The Netherlands National Institute of Public Health and Environmental Protection concluded that groundwater was threatened by pesticides in all European states. They reported that the EC standard for the sum of pesticides (0.5 μg liter^{-1}) will be exceeded on 65% of all agricultural land, and that the standard will be exceeded by more than an order of magnitude on 25% of the area (RIVM, 1992).

The National Water Quality Assessment (NAWQA) program of the US Geological Survey (USGS) represents the most comprehensive national-scale analysis to date of pesticide occurrence and concentrations in streams and groundwater of the United States (Gilliom *et al.*, 2006). This decade-long survey from 1992 to 2001 conducted assessments of 75 pesticides and 8 degradation products in surface water, groundwater, and sediments in 51 US major river basins and aquifer systems. At least one pesticide was detected in water from all streams studied, and pesticide compounds were detected throughout most of the year in water from streams with agricultural, urban, or mixed-land-use watersheds. Organochlorine pesticides (such as DDT) and their degradation byproducts were found in fish and bed-sediment samples from most streams in agricultural, urban, and mixed-land-use watersheds, and in more than half the fish from streams with predominantly undeveloped watersheds.

Pesticides were less common in groundwater than streams. They were found most frequently in shallow groundwater beneath agricultural and urban areas, where more than 50% of wells contained one or more pesticide compounds. Detections were often at low concentrations, and NAWQA personnel estimated that less than 10% of their monitored stream sites and about 1% of wells surveyed had concentrations greater than levels deemed to be high enough to affect human health.

Use of pesticides in developing countries is quite variable, ranging from none in much of Africa to extremely heavy use in intensive agricultural areas of Brazil and plantations of Central America. Pesticide use in the Brazilian state of Paraná is typical of developing countries undergoing rapid expansion of agriculture. Andreoli (1993) reports that Brazil had become the third largest user of agricultural pesticides by 1970, but conducted very little monitoring of their dispersal through the environment. One major study was conducted over the period 1976 and 1984 in the Paraná River basin, and showed that over 91% of *in situ* samples contained at least one pesticide or residue.

3. Industrial Emissions of Chemicals

Water is used by industry in a large variety of ways, many of which degrade its quality. The total withdrawal from surface water or groundwater by industry is usually much greater than the amount of water that is actually consumed, so the industrial effluent has potential for beneficial use if its quality is not impaired. The residual is commonly returned either by direct injection into a water body, disposal to a sewer, or disposal after treatment by an on-site wastewater treatment plant. In some cases, industrial effluent is recycled or reused directly on-site, either before or after treatment.

When industrial effluent is discharged directly into a water body without adequate treatment, a number of toxic chemicals can enter the water cycle. If the water is contaminated with heavy metals, they can attach to suspended particles and contaminate lake or stream sediment. Injected water that has a high level of organic matter can cause a rapid growth of algae, bacteria, and slime, followed by a depletion of the level of oxygen in the water. Whenever polluted effluent is injected into a water body, it contaminates a much larger volume of water as it mixes with the surroundings.

Industries and water quality regulators in some places still rely on dilution to disperse contaminants by mixing with unpolluted water until the levels of contaminant drop below harmful levels. This short-sighted policy is problematic for many reasons. Dilute levels of contaminant can bioaccumulate in the food chain, reaching toxic concentrations at higher trophic levels. Unregulated discharge by multiple sources can rapidly pollute large bodies of water to harmful levels, as well as cause oxygen depletion through organic matter additions.

In international river basins, intentional discharge or industrial accidents and spillages by one country can cause severe damage to downstream users in another country. In 1986, a fire in a pesticide-manufacturing plant in Basel Switzerland resulted in firefighters washing 30 t of pesticides and dyes into the Rhine River. Damage to the river ecosystem was extensive, and it interrupted water use of the river by the four countries adjoining it for months (Capel *et al.*, 1988).

Many municipalities around the globe have their drinking water supply impacted by industrial pollution, raising water treatment costs for the water supply utility. If irregular effluent discharges produce highly variable water quality, the water treatment plant may not be able to cope adequately with the contaminants. Industrial pollution may also indirectly affect water supplies by leaching of chemicals from solid wastes and by atmospheric deposition. A study of 15 Japanese cities, for example, showed that 30% of all groundwater supplies were contaminated by chlorinated solvents from industry. In some cases, the solvents from spills had traveled as far as 10 km from the source of pollution (UNEP, 1996). Many streams, rivers, and lakes in Europe are more acidic than they would naturally be, due to acidic deposition. In Scandinavia, for example, hundreds of lakes still suffer from acidification, and will take a long time to recover (European Environment Agency, 1997).

Exposure to heavy metals has been linked with developmental retardation, various cancers, and kidney damage. Exposure to high levels of mercury, gold, and lead has also been associated with the development of autoimmune disease, in which the immune system starts to attack its own cells, mistaking them for foreign invaders (Glover-Kerkvliet, 1995). Several studies have shown that exposure to lead can significantly reduce the IQ of children (Goyer, 1996). In some countries, heavy metal emissions are falling as a result of the removal of lead from petrol, improvements in wastewater treatment and incinerators, and improved industrial technologies. Significant further improvements could be achieved if the available technologies were more widely applied (European Environment Agency, 1998).

4. Natural Toxics

One of the greatest water quality challenges to manage is the accumulation of toxic chemicals that are dissolved out of native soil or rock material. The element posing the greatest threat to humans is arsenic. Arsenic is a natural part of the earth's crust in some parts of the globe, and may be found in groundwater underneath arsenic-rich rocks. Long-term exposure to arsenic via drinking water causes cancer of the skin, lungs, urinary bladder, and kidney, as well as other skin problems such as pigmentation changes and thickening (WHO, 1993). A public health limit of 10 μg liter^{-1} has been established by the World Health Organization and subsequently adopted by a number of countries, based on evidence from chronic exposure in arsenic-rich areas of the world. Although concentrations of arsenic in rivers are generally low, they can be found at high levels near geothermal activity or through discharge from arsenic-rich groundwater (Smedley and Kinniburgh, 2005).

A number of large aquifers in various parts of the world with arsenic levels at concentrations above 50 μg liter^{-1} have been linked to health problems. Regions suffering from high arsenic levels include parts of Argentina, Bangladesh, Chile, northern China, Hungary, the West Bengal region of India, Mexico, Romania, Taiwan, and parts of the Southwest United States. The problem is most severe in Bangladesh, where over 25% of the wells tested have revealed levels of arsenic above 50 μg liter^{-1}. It has been estimated that up to 77 million inhabitants of Bangladesh are at risk from drinking arsenic-contaminated water (Smith *et al.*, 2000).

Ingestion of excess fluoride in drinking-water can cause fluorosis, which affects the teeth and bones. Moderate exposure will cause dental complications, but long-term ingestion of large amounts can lead to potentially severe skeletal problems (WHO, 1993). Since some fluoride compounds in the earth's upper crust are soluble in water, fluoride is found in both surface waters and groundwater. In surface water, fluoride concentrations are usually low, but levels in groundwater can rise to more than 35 mg liter^{-1} depending on aquifer conditions.

Fluorosis is endemic in at least 25 countries across the globe. The total number of people affected is not known, but could number in the tens of million or higher. All states of India except in the northeast have reported cases of fluorosis, and 25–30 million people are estimated to be exposed to high fluoride intake, of which half a million suffer from skeletal fluorosis (UNICEF, 1999). In China, 300 million people are living in endemic areas of fluorosis, of whom 40 million have dental fluorosis and 3 million suffer from skeletal changes (Li and Cao, 1994).

Selenium is another natural constituent of certain rock and soil material that can be dissolved by percolating water. In 1983, incidents of mortality, congenital deformities, and reproductive failures in aquatic birds were discovered at Kesterson Reservoir, a US Department of the Interior (DOI) National Wildlife Refuge in western San Joaquin Valley, California. The cause of these adverse biological effects was determined to be poisoning by selenium carried by irrigation drainage into areas used by wildlife (Ohlendorf *et al.*, 1988). In the western United States, about 160,000 square miles of land, which includes about 4100 square miles of land under irrigation, has been identified as being susceptible to selenium leaching (Seiler *et al.*, 1999).

E. WATER FOR ECOSYSTEMS

A river needs to flow over its entire length to support the riparian ecosystems that depend on it. How much flow is required for ecosystem health is a matter of debate, and undoubtedly depends on the local conditions.

Falkenmark and Rockstrom (2004) indicate that roughly 30% of the base flow of a river should remain untouched. This amounts to 3780 km^3 of the 12,500 km^3 available supply. Postel *et al.* (1996) arrived at a number of 2350 $\mathrm{km}^3\ \mathrm{year}^{-1}$ required for instream uses by a different method.

Human appropriation and use of water has caused enormous damage to ecosystems during the last half century, through activities such as draining of wetlands, damming of rivers, and pollution of lakes and streams. Participants in the Millennium Ecosystem Assessment concluded that humans have changed terrestrial and aquatic ecosystems more rapidly and extensively over the past 50 years than in any comparable period of time in human history, largely to meet rapidly growing demands for food, freshwater, timber, fiber, and fuel. Their analysis showed that 15 of the 24 ecosystem services examined during the Millennium Ecosystem Assessment are being degraded or used unsustainably (Millennium Ecosystem Assessment, 2005). The degradation or loss of ecosystem function has huge economic implications, since freshwater ecosystems provide several trillion dollars in annual services (Postel, 1997).

1. Stream Flow Modification

A major analysis of international water resources was made recently by the Global International Waters Assessment (GIWA) project of the UN Environmental Program. Nineteen GIWA regional teams identified stream flow modification as having severe impacts, particularly in sub-Saharan Africa, North Africa, Northeast Asia, Central America and Europe, and Central Asia. On a global scale, the most widespread and adverse consequences result from the modification of stream flow by dams, reservoirs, and river diversions, as well as by land-use changes in the catchment area. Downstream ecosystems and riparian communities are severely impacted by changes to the flow regime of international rivers (UNEP, 2006).

Today, dams and reservoirs intercept about 35% of river flows as they head toward the sea—up from 5% in 1950 (Postel, 2005). Many rivers are so overused that they run dry before reaching the sea for extended periods, causing severe damage to fisheries and coastal zones. Rivers falling into this category include the Huang He (Yellow River) in China, the Indus and Ganges in South Asia, the Nile in Africa, the Syr Darya in Central Asia, the Chao Phraya in Thailand, and the Colorado in the western United States (Postel, 1999).

2. Wetlands Loss

Wetlands provide a wealth of valuable ecosystem services and support diverse habitat. Some estimates show that half of the world's wetlands have been destroyed by humans in the last 100 years. Much of this loss occurred in northern countries during the first 50 years of the century, but since the 1950s increasing pressure for conversion to alternative land use has been put on tropical and subtropical wetlands. Examples of the impacts of the loss and degradation of wetlands include: impaired or reduced water supply, loss of water flow regulation and flood control, saline intrusion into groundwater and surface water, increased erosion, reduced sediment and nutrient retention, and loss of capacity for pollution removal (Davies and Claridge, 1993).

Land conversion for agricultural production is the principal cause of wetlands destruction worldwide. Between 56% and 65% of the available wetland had been drained for intensive agriculture in Europe and North America by 1985. The figures for tropical and subtropical regions were 27% for Asia, 6% for South America, 2% for Africa, and a total of 26% worldwide. Future predictions show the pressure to drain land for agriculture intensifying in these regions (Moser *et al.*, 1996).

F. Groundwater Overdraft

Groundwater residing below the near subsurface was an unexploited commodity for most of human history, until technological development allowed it to be extracted from great depths. But with that innovation, it has become a reliable source of supply for a variety of municipal, industrial, and agricultural needs. Annual groundwater use for the world as a whole has been estimated at 750–800 km^3 (Shah *et al.*, 2000b), a relatively small fraction of the total use (Table II). However, most of the world's cities and towns depend on groundwater to supply at least part of their needs. For example, approximately half the population of the United States relies on groundwater for drinking, and more than 90% of rural residents obtain their water from groundwater through wells or springs (US EPA, 2006). Groundwater also provides a significant part of the industrial water demand in most countries. In some of the poorest and most populous regions of the world, particularly in South Asia, groundwater has become critical for feeding the population. In India, for example, some 60% of the irrigated food grain production now depends on irrigation from groundwater wells.

Groundwater overdrafting occurs when the rate at which water is extracted from an aquifer exceeds the rate at which the aquifer is replenished or recharged. Chronic overdraft causes persistent lowering of water tables, which leads ultimately to economic exhaustion of the aquifer. Some aquifers have no significant recharge at all and in these instances the water is available on a one-time basis much like stock resources in a mine. The extent of persistent groundwater overdrafting on a global basis is difficult to estimate because of limited data and extensive variability in groundwater levels over time and space. Postel (1999) calculated that as much as 163 km^3 year^{-1} of persistent overdraft is occurring globally, about 80% of which was occurring in India and China and most of the rest in the Americas and Africa.

The implications of overdraft are not always clear. Intermittent overdraft, where periods of overdraft alternate with periods of net recharge, is generally an acceptable practice. Intermittent overdrafting is a common way of coping with drought, for example. By contrast, persistent overdrafting is more problematic and has serious long-term impacts. There is great concern over the fact that overdraft is not only unsustainable but tends to be self-terminating when water table depths fall below the level from which it is economical to pump. In such cases, accustomed levels of water supply will have to be reduced unless alternative sources of water can be found. In many such instances, alternative sources of supply are not available (Vaux, 2007). Since much of the water that is thought to be overdrafted is primarily used for irrigation, it can be argued that close to 500 million people are being fed with food grown by a water supply that could disappear in the future. One analysis concluded that as much as 25% of India's grain harvest could be in jeopardy (Seckler *et al.*, 1999).

An analysis of persistent overdrafting cautions that the uncertainties in making estimates of the extent of this practice are too great to support a quantitative analysis from the existing database (Moench *et al.*, 2003). These authors argue that the lack of comprehensive monitoring as well as the short time series available where adequate monitoring has occurred means that conclusions about the presence or absence of overdraft are not based on solid empirical evidence in many instances. In addition, these authors question the connection between groundwater overdraft and food security, noting that trade may produce alternative sources of food and citing a number of other factors that may tend to disconnect groundwater overdraft from the production of food.

A final concern about groundwater and its management relates to the role of groundwater in providing environmental amenities and services. Glennon (2002) notes that estimates of safe yield (the yield that just equals recharge) fail to account for environmental uses of groundwater and the interconnectedness of groundwater and surface water in many instances. The fact that groundwater is treated as a common pool resource in many parts of the world means that environmental uses tend to be ignored and little attention is given to overdrafting. The lack of adequate governance of groundwater resources is frequently cited as a reason for suspecting that such resources are overexploited (Glennon, 2002).

The brief overview provided in this section has identified a number of water-related problems in various regions of the world. These problems threaten to diminish the available supply and pose severe threats to the integrity of aquatic ecosystems throughout the world. Even if water demands were to remain static these problems suggest that it may be difficult to continue meeting them as we have in the past. However, even more serious challenges lie in the years ahead as the world adds billions more in population which will augment water demand even as available supplies are shrinking. In Section III, projected changes in population and the impacts of these changes on water resources and their quality are discussed.

III. POPULATION TRENDS AND WATER STRESSES

A single snapshot in time of water resource supply, quality, and consumption for a region does not provide sufficient information to develop a water management strategy. Many factors that influence water resources are time dependent, so it is necessary to characterize temporal trends as well as to evaluate the water balance at any given time. Water resource availability and quality are already serious problems in certain parts of the world today, and other regions that are currently not under stress could face shortages in the next few decades as demands increase.

The first step in making a credible assessment of future water supplies and demands is to forecast population growth, which can be done relatively accurately in the short run, but which depends on assumptions that make estimates progressively more uncertain for later times. Lutz *et al.* (2001) estimated world population growth over the next century together with the 80% confidence limits, and found that the mean population would level off by the second half of the century after reaching a maximum of a little more than 9 billion. However, by mid century, the 80% confidence limits of the mean projection ranged over nearly three billion. We will use the US Census international database (US Census, 2006) for population estimates in this chapter unless otherwise noted, and confine our discussion to the first half of the twenty-first century. Over that period the US Census prediction agrees reasonably well with the mean curve estimated by Lutz *et al.* (2001). According to the US Census estimate, global population will rise from 6.1 billion to 7.9 billion between 2000 and 2025, and to 9.2 billion by 2050.

A. Water-Short and Water-Stressed Countries

The FSI (Section II.B) classified 29 countries with a population of 460 million as being in either a water-stressed or a water-scarce situation in 1995 (Table III). By 2025, this number rises to 47 countries and 2.8 billion people (Table VI), including 19 countries with annual assets that fall below the water barrier of 500 m^3 $year^{-1}$ per person (Table VII).

An additional factor that needs to be taken into account in assessing the effect of population growth on water supply is where the growth is occurring

Table VI
Population and Numbers of Countries Predicted to Experience Water Stress or Scarcity by 2025 According to the FSI

Category	Countries	Population (millions)
Water scarce	29 (17)	802 (218)
Water stressed	19	2027
Water scarce or stressed	47	2829

Number in parentheses indicates countries below water barrier of PWR $< 500\ \mathrm{m}^3\ \mathrm{year}^{-1}$ per person. Data adapted from Population Reports (1998).

Table VII
Countries Predicted to Experience Water Stress or Scarcity by 2025 According to the FSI

Below water barrier PWR $< 500\ \mathrm{m}^3\ \mathrm{year}^{-1}$	Water stressed PWR $= 500$–$1000\ \mathrm{m}^3\ \mathrm{year}^{-1}$	Water scarce PWR $= 1000$–$1700\ \mathrm{m}^3\ \mathrm{year}^{-1}$
Algeria	Comoros	Belgium
Bahrain	Cyprus	Burkina Faso
Barbados	Egypt	Eritrea
Burundi	Ethiopia	Ghana
Cape Verde	Haiti	India
Israel	Iran	Lebanon
Jordan	Kenya	Lesotho
Kuwait	Malawi	Mauritius
Libya	Morocco	Niger
Malta	Somalia	Nigeria
Oman	South Africa	Peru
Qatar	UAE	Poland
Rwanda		South Korea
Saudi Arabia		Syria
Singapore		Tanzania
Tunisia		Togo
Yemen		Uganda
		United Kingdom
		Zimbabwe

relative to available local water resources. Figure 4 shows the historical and projected population growth of the world and various subdivisions. Several features are worth noting. First, virtually all of the projected population growth between the present and 2050 is expected to occur in developing countries, a number of which are already experiencing water shortages. Second, the population of water-short countries (PWR $< 1700\ \mathrm{m}^3\ \mathrm{year}^{-1}$) is a small fraction (~7.5%) of the world population in 1995, but a significant fraction (~36%) by 2025, largely due to India falling below the threshold PWR.

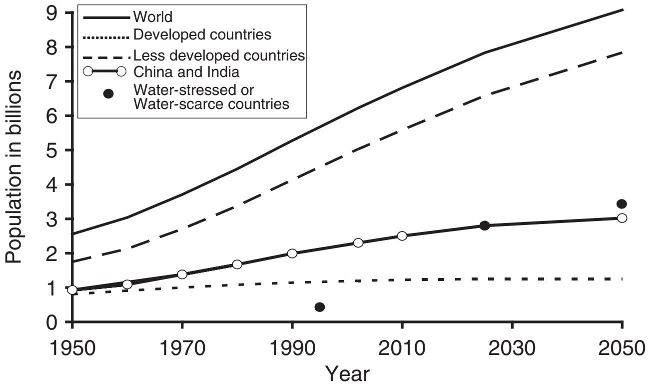

Figure 4 Historical and projected population growth of population subgroups. Water-stressed or -scarce countries are those whose per capita resources are below 1700 m^3 $year^{-1}$. (Data from US Census, 2006).

China and India together constitute over 35% of the world's population, so their water use and food requirements will have a dominant influence on global trends. Figure 5 shows the population and per capita water resources for these two countries between 1950 and 2050, based on the assumption that total water resources will remain constant in the future. By 2015, India will drop below the FSI threshold of 1700 m^3 $year^{-1}$, reaching a low of 1300 m^3 $year^{-1}$ by mid century. China approaches but remains above the threshold as its population levels off. However, each country has wet and dry regions, so the national average can be misleading. China has approximately half of its population in the north, where only 20% of its water resources are found. Thus, if North China was viewed as a separate country, its per capita resources would be only 40% of those shown in Fig. 5, and would dip to a low value of 770 m^3 $year^{-1}$, falling well below the FSI threshold.

Although the various indices for expressing water scarcity have some common elements, they do not produce the same classification when applied to the countries of the world. Figure 6 shows a comparison of three indices on a group of 38 countries considered water short in 2025 by some criterion. All of the 38 countries are classified as water stressed by the FSI, but only 22 of them by the UN criterion. Even fewer countries (14) are classified in the most stressed water group 1 by the method used by Seckler *et al.* (1998). Reasons for the variances in classification are due to the different criteria used. For example, Burundi has only 267 m^3 $year^{-1}$ of per capita annual water resources, making it extremely water scarce by the FSI, but is using only 9% of it in annual withdrawals, which causes it to be rated as unstressed by the other criteria.

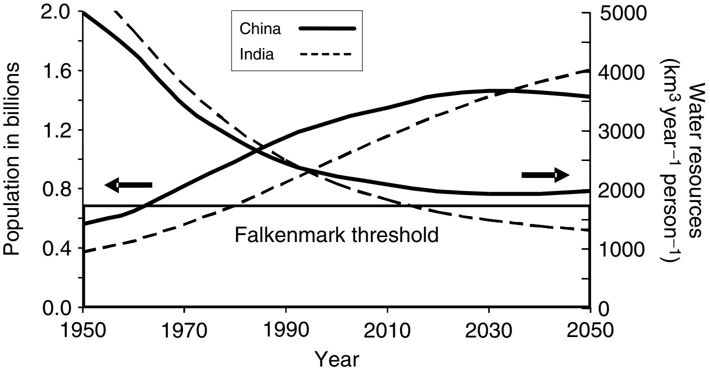

Figure 5 Population growth and per capita water resources of China (solid curve) and India (dashed curve). Shaded region marks the zone with water resources below the Falkenmark stress indicator threshold of 1700 m^3 year^{-1}.

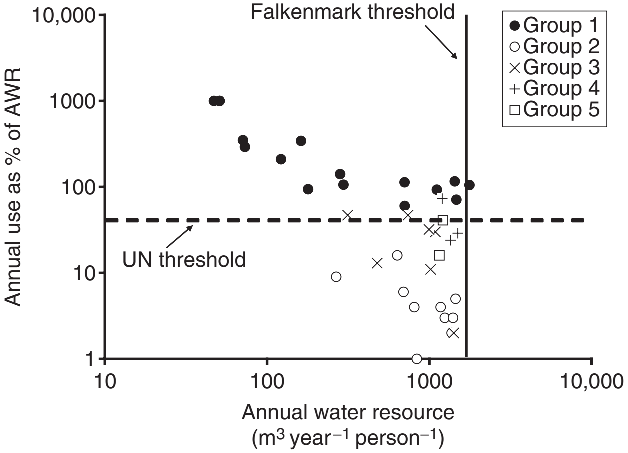

Figure 6 Classification of the degree of water scarcity of a country in 2025 according to various benchmarks of water use and water availability. The Falkenmark threshold is 1700 m^3 year^{-1} per person and the UN threshold is 40% annual use of the available water resource.

Table VIII summarizes 29 countries that consume more than 20% of their annual water resources in a given year. Many of the countries listed in Table VII as being water scarce or stressed according to the FSI do not appear in Table VIII, usually because irrigation is not required to grow crops and hence less water per capita is needed for food production. This shows that the indices by themselves cannot adequately classify whether a country is likely to experience hardship in the next few decades due to inadequate water

Table VIII
Groupings of Countries According to the Fraction of Annual Water Resources Consumed in a Given Year

W/AWR > 1.0	0.5 < W/AWR < 1.0	0.3 < W/AWR < 0.5	0.2 < W/AWR < 0.3
Bahrain	Belgium	Afghanistan	India
Jordan	Egypt	Algeria	Japan
Kuwait	Iraq	Cyprus	Lebanon
Libya	Israel	Iran	Sri Lanka
Oman	Pakistan	South Korea	Swaziland
Qatar	Yemen	Morocco	
Saudi Arabia		Singapore	
Tunisia		South Africa	
UAE		Syria	

resources. For example, a country with a low PWR that can afford to import food may have a more than adequate supply of water for all other uses. In contrast, poor countries with inadequate PWR will have difficulty finding the capital required to import food, and may face starvation in the future if they do not have the means to grow what they need.

There is clearly no single strategy adequate for dealing with future water challenges on a global level. Optimization of the conflicting requirements for water by the agricultural, industrial, urban, and environmental sectors will require a systems perspective driven by both short-term needs and a long-term perspective.

B. URBANIZATION TRENDS

According to the 2004 assessment of the United Nations, the projected change in world population between 1995 and 2030 will be 2.51 billion, while at the same time the increase in urban population will be 2.44 billion. While much of the change is due to urban migration, it is equivalent for planning purposes to assume that virtually all of the increased population in the next half century will live in cities. This trend will significantly raise the proportion of the population in urban areas of developing countries (Fig. 7). Cities are also becoming much larger, with a number reaching mega-city size, denoting an urban area of more than 10 million (Table IX).

Jenerette and Larson (2006) estimate that the number of cities with more than 5 million residents is expected to increase globally from 46 to 61 between 2015 and 2030, with disproportionate increases in Asia and Africa. Large cities place special demands on water resources because of the high population density, and the challenges presented in maintaining adequate sanitation. These authors analyzed the resource requirements of the 524 urban

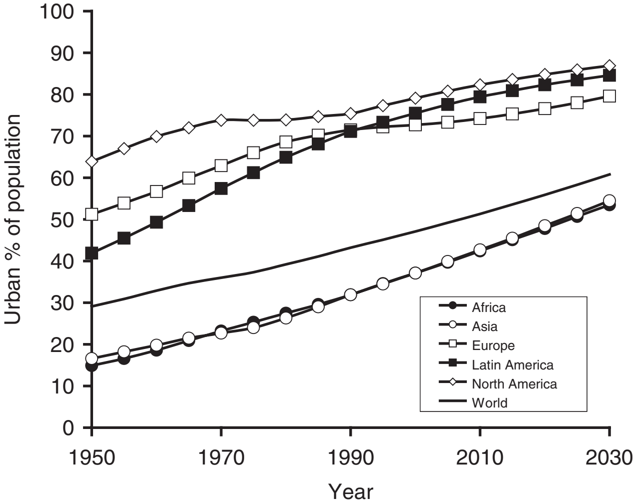

Figure 7 Percentage of the population of various population sectors residing in cities as a function of time.

Table IX
Number of Mega Cities in the World at Different Times

Year	Population > 10 million	Population > 15 million	Population > 20 million
1985	9	2	1
2000	18	5	1
2015	22	11	4

regions with populations greater than 750,000 as of 2000 using an ecological footprint (EF) analysis. The EF calculates the land area required to provide sustainable services to the urban unit. Table X shows how the EF required to provide water resources has grown over time, and that the largest of the mega cities in water-short regions have enormous EF. Saudi Arabia, for example, had five cities with EF ranging from 1.4 to 2.4 million km^2. The study also suggested that cities with a high EF are also especially sensitive to climate change.

Providing adequate water for urban uses in metropolitan areas with huge populations in the future will be extraordinarily challenging. Many regions now provide services only by extracting groundwater at rates greatly in excess of recharge, which not only jeopardizes future availability but also causes ancillary problems such as land subsidence and increased vulnerability to aquifer contamination. Other metropolitan areas, while currently self-sufficient, have no obvious sources of supplemental supply to support population growth.

Table X
Mean Ecological Footprint for Water Resources Required to Provide the World's Cities of Greater Than 750,000 Population (Jenerette and Larson, 2006)

Baseline scenario (year)	Mean footprint area (km^2)	Total urban water footprint (km^2)
1950	29,937 (6.23)	15,686,988
2000	35,397 (5.44)	18,548,028
2015	38,400 (5.18)	20,121,600

Coefficient of variation of estimate is given in parentheses of column 2.

C. INDUSTRIAL AND MUNICIPAL WATER DEMANDS

Municipal water demands consist of the water withdrawals made by the populations of urban areas for domestic use plus withdrawals for industrial, public, and commercial uses. In many cities, a considerable volume of water is applied to vegetable gardens and residential landscapes. The volume of public water use depends on population, the level of services and utilities, the availability of conveyance and supply infrastructure, and climatic conditions (Shiklomanov, 2000).

In industrially developed countries of Europe and North America, per capita domestic water withdrawal is of the order of 500–800 liter day^{-1} (Shiklomanov, 2000). In contrast, it is only about 50–100 liter day^{-1} in developing agricultural countries of Asia, Africa, and Latin America, and 10–40 liter day^{-1} in regions with insufficient water resources (Gleick, 1996). Although it is tempting to suggest that economic development is associated with increasing per capita water use, Gleick (2006) has shown that, at least in the United States, per capita water consumption has been falling.

Water in industry is employed for cooling, transportation, as a solvent, and as an ingredient of finished products. The dominant user is electric power generation, which requires a great amount of cooling water. Other heavy industrial water users are the chemistry and petroleum chemistry industries, the wood pulp and paper industries, the metallurgy industry, and machine building. The water needed by a given industry depends mainly on whether the water withdrawn is passed once through the system or circulated internally. With a circulating system, the water is cooled, treated, and routed back to the water supply system after use, whereas effluent from a once-through system is returned to the source water. In addition, many industries in developed countries find it economical to recycle process water in order to meet prevailing pollution discharge regulations (Shiklomanov, 2000).

Although the consumption of water for industrial and public use is considerably less than for agriculture (Table II), it is not insignificant and will become a challenge to manage in certain regions in the future. Figure 8

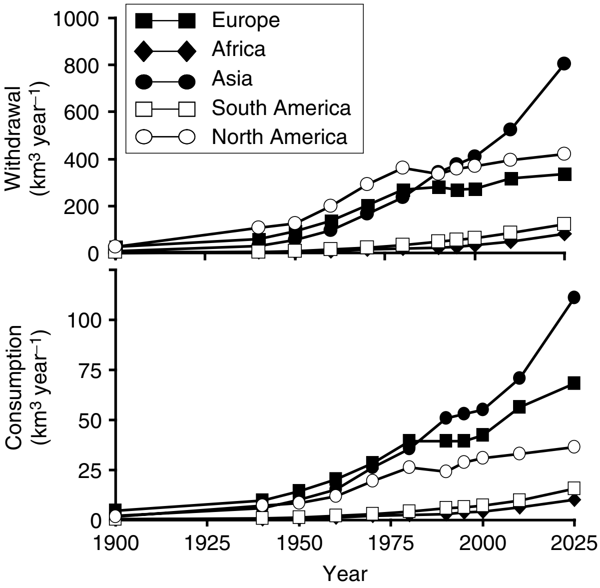

Figure 8 Withdrawal and consumption of water for industrial and domestic purposes as a function of time for various continents. Data after 1995 is projected (Data taken from Shiklomanov, 1997).

shows the withdrawal and consumption of water as a function of time by the municipal and industrial sectors in the five major continents (Shiklomanov, 1997). The projected increases for the early part of the twenty-first century reflect both the relative population stability in the developed countries and the explosive growth in urbanization and industrialization projected for Asia. Also notable is the huge difference between consumption and withdrawal, which can be misleading if the water returned to the surface water or groundwater supply by the municipal and industrial sectors is in a degraded state from pollution.

The projected increases in global withdrawal and consumption of water by various sectors between 1995 and 2025 are given in Table XI. Note again that the withdrawal of water by the municipal and industrial sectors during this time frame is comparable to the withdrawal for irrigation by agriculture, but actual consumption is only about 20%. Reservoir losses from evaporation are also substantial. When there is competition for water between sectors, agriculture could lose significant food production capability in a region. For example, assuming 1200 m^3 $year^{-1}$ to feed one person, the additional 681 km^3 $year^{-1}$ of water withdrawn for municipal and industrial use between 1995 and 2025 represents the water needed to grow food for nearly 570 million people.

Table XI
Projected Increase in Water Withdrawal and Consumption in km^3 $year^{-1}$ by Various Sectors Between 1995 and 2025 (after Shiklomanov, 2000)

Sector or use category	Withdrawal increase (km^3 $year^{-1}$)	Withdrawal increase (% of total)	Consumption increase (km^3 $year^{-1}$)	Consumption increase (% of total)
Agriculture	685	47.3	499	72.3
Municipal	263	18.2	24.3	3.5
Industry	418	28.9	86.4	12.5
Reservoir losses	81	5.6	81	11.7
Total	1447	100.0	690	100.0

D. TRANSBOUNDARY ISSUES

Water does not respect international boundaries. Today, some 146 countries of the world share a river with at least one other nation. There are 261 international river basins whose drainage areas span more than one country, covering in total some 45% of the land area of the planet (Wolf *et al.*, 1999). Table XII shows the number of countries sharing various international river basins, led by the Danube which flows through 17 nations in Europe. A number of these shared basins operate without treaties governing their use. The absence of treaties or operating agreements frequently leads to overextraction, conflicting management plans, and border tensions. In the most extreme cases, these conflicts have reached the level of hostility though not violence. Table XIII lists five of the more serious river basin conflicts around the world. Each is briefly discussed in the following sections.

1. Jordan River

The Jordan River drains part of Israel, Jordan, Lebanon, and Syria. It is a small water body, extending only 93 km from its source waters in Lebanon to its final discharge into the Dead Sea. Each of the three streams forming the river's headwaters was originally in a different country, but since the end of the 1969 war Israel has controlled all of the stream areas. The upper reach of the Jordan drains into Lake Tiberias (also called Sea of Galilee or Lake Kinneret), which at 21 km in length and 13 km in width is Israel's largest freshwater body. The lake's outflow moves to the Dead Sea along the Jordan River valley.

The Jordan River has two principal tributaries, the Yarmouk originating in Syria and the Zarqa which flows out of Jordan. Two major diversion works extract water from the river, Israel's National Water Carrier and

Table XII
Number of Countries Sharing a River Basin (Wolf *et al.*, 1999)

Countries	Basins	Name of basins
17	1	Danube
11	2	Congo, Niger
10	1	Nile
9	2	Rhine and Zambezi
8	2	Amazon, Lake Chad
6	8	–
5	3	–
4	17	–
3	49	–
2	176	–

Table XIII
Examples of Serious International River Basin Disputes and the Countries Involved

River	Countries involved
Jordan	Israel, Jordan, Lebanon, Syria
Tigris-Euphrates	Iraq, Syria, Turkey
Nile	Egypt, Ethiopia, Sudan
Indus	India, Pakistan
Ganges	India, Bangladesh

Jordan's East Ghor Canal. The National Water Carrier transports water from Lake Tiberias through a network of pipes to Tel Aviv and the Negev, while the East Ghor Canal diverts water from the Yarmouk River to agricultural areas in the Jordan Valley (McCafferty, 1998). The basin has no treaty governing its use, although a US-brokered agreement to allocate the Jordan and Yarmouk's flows (known as the Johnston Plan) was reached in the 1950s by technical representatives from all countries but was never ratified by the governments concerned. That agreement would have given Jordan ~19% of the flow of the upper Jordan River and 75% of the Yarmouk.

Since the Six Days' War, however, due to its downstream position on the Jordan River and its weak strategic standing on the Yarmouk, Jordan has been greatly disadvantaged in its water use opportunities. Israel has virtually monopolized the waters of the Upper Jordan since the late 1960s, with only a highly polluted residual of wastewater flowing to the Dead Sea. Jordan's use of the Yarmouk has also been restricted, both by Israeli withdrawals to restock Lake Tiberias and by Syria's increasing upstream use. As a consequence, Jordan is only using about 25% of the Yarmouk's flow, which is only one third of the allocation it was granted in the Johnston plan (Libiszewsk, 1995). Despite adopting a number of conservation and water efficiency practices, Jordanian farmers in the lower valley are struggling to survive on the supply of water available (Ayadi, 2006).

The Jordan River Basin is complicated further by the fact that both the West Bank and Gaza Strip of Palestine lie within the Basin and its service area. Per capita water availability in Palestine is a fraction of what is available to Jordan and an even smaller fraction of what is available to Israel. This makes the problem of allocating the very scarce waters of the basin among different users and claimants even more difficult (National Research Council, 1999a). One recent study shows that water could be allocated according to its economic value, thereby minimizing the costs and disruptions now attributable to a lack of water. This study also suggests that desalination is not necessarily needed on a broad scale to address the region's water problems (Fisher *et al.*, 2005).

2. Tigris-Euphrates Basin

The Tigris and Euphrates rivers are often treated as one basin because they merge before reaching their final destination. Both rivers originate in the mountains of Turkey and flow through or at the boundary of Syria before entering Iraq. Iraq is heavily dependent on the two rivers for its water supply, which provides the only source for much of its population. Turkey is currently constructing a large water project on the Euphrates in southeastern Anatolia, known as the Greater Anatolian Project (GAP). The GAP will eventually consist of 21 dams to be used for hydroelectric power production and the irrigation of over a million hectares of agricultural land. When complete, the dam system could cause Syria to lose up to 40% and Iraq up to 90% of their water from the Euphrates (McCafferty, 1998).

The three riparian nations have had some success in addressing their differences over the project and other water issues peacefully. Bilateral agreements exist between Turkey and Iraq and between Syria and Iraq on certain issues in their water relations. However, the GAP poses a significant environmental threat to Turkey's downstream neighbors in the future.

3. Nile River

The Nile is the longest river in the world, draining an area over 3 million km^2 in 10 countries. About 85% of the Nile's flow originates in Ethiopia as the Blue Nile, with the remainder coming from the White Nile which begins in Tanzania. Until recently, use of the Nile was dominated by Egypt, which is dependent on its flow for virtually all of its water. Egypt has a bilateral treaty with Sudan, in which Egypt is entitled to 55.5 km^3 of annual flow, and Sudan an additional 18.5 km^3. The other countries with access to the Nile do not have an agreement governing its water use.

Egypt currently is using all of its allocation, and its population is rising rapidly. It has plans to expand its irrigation by at least 1 million ha over the next 20 years, which at current use rates would require an additional 8 km^3 of water (Postel, 1999). Ethiopia would like to build dams for hydroelectric power and to provide water to irrigate substantial land in its country, activities which have the potential to divert as much as 7.2 km^3 $year^{-1}$ of flow from the Nile.

The Nile is virtually fully appropriated and very little flow reaches the Mediterranean Sea, which has drastically altered the aquatic habitat of the delta. The situation is further complicated by the fact that the other nations along the Nile have never recognized the Egypt–Sudan water agreement because they were not involved in its negotiation.

Although tensions over water have nearly led to armed intervention in the past, more recently the countries involved have developed a mechanism for regional cooperation. The Nile Basin Initiative, launched in February 1999, is a regional partnership within which countries of the Nile Basin have united in common pursuit of the long-term development and management of Nile waters. The Initiative partnership is developing consensus on a basin-wide framework and is guided by the countries' shared vision to achieve sustainable socioeconomic development through the equitable utilization of, and benefit from, the common Nile Basin water resources (Foulds, 2002). The early results of these efforts seem promising but many difficult issues remain to be addressed.

4. Indus River

The Indus River, which originates in Tibet and flows 2900 km through India and Pakistan, has been the subject of controversy since the India–Pakistan division in 1947. The partition left part of the basin in each country, with the majority of the canal system and irrigated lands residing in Pakistan. Early conflicts over water were frequent, and even led to India temporarily stopping the supply of water to the canals in Pakistan in 1948. The World Bank was successful in getting both countries to adopt a comprehensive water agreement known as the Indus Waters Treaty in 1960, in part because it sponsored projects that would increase the water allocation to both countries. With minor exceptions, the treaty gives India exclusive use of all of the waters of the Eastern Rivers and their tributaries before the point where the rivers enter Pakistan. Similarly, Pakistan has exclusive use of the

Western Rivers. Pakistan also received one-time financial compensation for the loss of water from the Eastern Rivers. Although the treaty is not legally binding, it has had the effect of quelling water disputes in this region for over 40 years (McCafferty, 1998). However, recent declines in the flow of the Indus have increased stresses, particularly in water-short Pakistan.

5. Ganges River

The Ganges originates in the Himalayas and flows through India to Bangladesh, where it joins the Brahmaputra to form the Padma, which empties into the Bay of Bengal. Between 1961 and 1975 India constructed a dam just upstream from the Bangladesh border, in order to divert water to Calcutta. This action left Bangladesh short of irrigation water needed in the dry months, of water needed to prevent siltation and subsequent flooding of the river, and of water needed to prevent seawater intrusion from the Bay of Bengal. Bangladesh subsequently appealed to the general assembly of the United Nations, and the countries eventually were persuaded into adopting a plan known as the 1977 Agreement on Sharing of the Ganges Waters, which allocated flow during the dry season.

The vast majority of water disputes involving international basins have been resolved without armed conflict. Researchers at Oregon State University have compiled a dataset of every reported interaction (conflictive or cooperative) between two or more nations that was driven by water in the last half century. The findings show that cooperation—not conflict—is the norm. In the last 50 years, only 37 international water disputes have involved violence, and 30 of those occurred between Israel and one of its neighbors. Outside of the Middle East, researchers found only 5 violent events while 157 treaties were negotiated and signed. They also found that over 70% of the 1735 water-related events recorded between nations were devoid of any conflict (Wolf, 1998).

E. PROJECTED WATER DEFICIT UNDER BUSINESS AS USUAL PRACTICES

There are already serious water deficits in certain parts of the planet today, and continuation of current policies and trends will create many more in the future. Since the increase in population between 1995 and 2025 is expected to be ~2.2 billion, per capita consumption patterns may be extrapolated to project the water that would be used in that year if current patterns of use and consumption are maintained in the face of significant population and economic growth. Assuming an average global water use for food production of 1200 m^3 $year^{-1}$ per person (Rockstrom *et al.*, 1999), the population increase implies that an additional 2740 km^3 $year^{-1}$ of water would be required to grow the food needed. Adding the 762 km^3 year^{-1} increase projected for domestic use, industrial use, and reservoir losses from Table XI, we obtain about 3500 km^3 year^{-1} of new water required to provide for the population of 2025.

Beyond merely feeding the increased population, Falkenmark and Rockstrom (2004) calculate that an additional 2200 km^3 year^{-1} of freshwater will be needed to eradicate malnutrition in the 2050 population. If we assume that half of this can be obtained by 2025 and the remainder by 2050, then an additional 4600 km^3 year^{-1} of freshwater will be required by 2025 to accommodate human needs. Table XIV summarizes these estimates. If the additional 1.2 billion population increase between 2025 and 2050 proves correct, another 1560 km^3 year^{-1} would be utilized by 2050 for food, an additional 430 km^3 year^{-1} needed for cities and industry, and the remaining 1100 km^3 year^{-1} required to alleviate malnutrition for a total increase of 3090 km^3 year^{-1} between 2025 and 2050. This leads to the staggering conclusion that nearly 7700 km^3 of *additional water* would have to be found by 2050 to supplement global supplies at the 1995 level. Not much of this needed water can come from expanded irrigation operations. Falkenmark and Rockstrom (2004) estimate that irrigation water use can be increased by not more than 800 km^3 year^{-1} through expansion of agricultural land and improvements in production efficiency. The remaining water must come from other sources, additional rainfed agriculture, or through increased efficiency and conservation efforts.

The numbers cited above merely represent an extrapolation of the business as usual policies and employ average estimates for all segments of the population. This extrapolative "requirements" approach to water planning and forecasting has proved to be notoriously unreliable. To some extent, the quantities of water used in different sectors are a matter of choice. And, within boundaries, capital and labor can be substituted for water. Additionally, there are almost always opportunities to improve the productivity of water, many of which result in water savings (National Research Council, 1999a). For example, a reanalysis of the water needed to feed the future population has been made by Rockstrom *et al.* (2007), and demonstrates that

Table XIV

Water Requirements in km^3 year in the Future Relative to 1995 Under Business as Usual Assumptions with No Changes in Consumption Patterns

Time period	Food production	Municipal and industrial[a]	Hunger eradication[b]	Total
1995–2025	2740	760	1100	4600
2025–2050	1560	430	1100	3090
1995–2050	4300	1190	2200	7690

[a] Includes reservoir losses.

[b] Assumes half alleviated by 2025 and the rest by 2050.

considerably less water may be required if additional factors are taken into account. In their new study, they assume that countries producing food on the low end of the yield spectrum will be able to increase yields substantially in the future, and that they will experience proportionately higher benefits from these yield increases because the additional biomass will lower evaporative losses. They also analyze separately the vegetative and animal portions of the diet and distinguish between irrigated feedland and grazing contributions. Their analysis concluded that 1910 $\text{km}^3\ \text{year}^{-1}$ additional water equivalent of needed food would have to be provided by cultivated rainfed land by 2025. Although this number is far below the figure obtained from simple extrapolation of current consumption rates and efficiencies, it still represents a huge gap that is likely to be filled only by impinging on natural ecosystems and their needed resources.

F. Threats to Ecosystem Health

Perhaps the greatest threat posed by projected freshwater scarcity in the future is to terrestrial ecosystems. If business as usual policies are continued into the future, more water will be diverted from rivers, more wetlands will be drained, more forests will be felled for additional cropland, more agricultural pollution will stress aquatic organisms, and additional dams will be constructed. As of 1995, humans appropriated 54% of the freshwater in lakes, lagoons, rivers, and streams (Postel *et al.*, 1996). By 2025, that value could reach 70% (Postel, 1998), which would require utilizing the entire flow of rivers in many regions.

Habitat destruction, water diversions, and pollution are contributing to sharp declines in freshwater biodiversity. Globally, the world has lost half of its wetlands, with most of the destruction occurring in the past half century. Destruction of habitat is the largest cause of biodiversity loss in almost every ecosystem, but biologists have found that most of the plant and animal extinctions have been those species dependent on freshwater and related habitats. One-fifth of all freshwater fish are threatened or have recently become extinct. On continents where studies have been done, more than half of amphibians are in decline, and more than 1000 bird species are threatened (Hinrichson, 2003).

The competition between people and wildlife for water is intensifying in many of the most biodiverse regions of the world. Of the 35 biodiversity hot spots designated by Conservation International (C2006), 10 are located in water-short regions. These regions—including Mexico, Central America, the Caribbean, the western United States, the Mediterranean Basin, southern Africa, and southwestern China—house an extremely large number of threatened species.

The services that freshwater ecosystems provide to humans such as fisheries, flood protection, recreation, and wildlife are estimated to be worth trillions of US dollars annually (Constanza *et al.*, 1997; Postel and Carpenter, 1997). A global assessment of the status of freshwater ecosystems (Revenga *et al.*, 2000) showed that their capacity to provide the full range of such goods and services appears to be drastically degraded. Many freshwater species are facing rapid population decline or extinction, and yields from many wild fisheries have dwindled as a result of flow regulation, habitat degradation, and pollution.

Much of the damage is due to inadequate flow in rivers as a result of human diversion and consumption. The environmental water requirement (EWR) required to maintain riparian ecosystem health has been estimated to range from 20% to 50% of the mean annual river flow in a basin, depending on local climate and conditions. Even at estimated modest levels of EWR, parts of the world are already or soon will be classified as environmentally water scarce or stressed. The total population living in basins, where modest EWR levels are already in conflict with current water use, is over 1.4 billion and this number is growing (Smakhtin *et al.*, 2004).

Over the past 50 years, humans have changed ecosystems more rapidly and extensively than in any comparable period in human history, largely to meet rapidly growing demands for food, freshwater, timber, fiber, and fuel. The changes that have been made to ecosystems have contributed to substantial net gains in human well-being and economic development, but these gains have been offset by degradation of many ecosystem services, increased risks of nonlinear changes, and tragic exploitation of some of the world's poorest peoples. These problems, unless addressed, will substantially diminish the benefits that future generations obtain from ecosystems.

Approximately 60% (15 of 24) of the ecosystem services examined during the Millennium Ecosystem Assessment are being degraded or used unsustainably, including freshwater, capture fisheries, air and water purification, and the regulation of regional and local climate, natural hazards, and pests (Millennium Ecosystem Assessment, 2005). The full costs of the degradation of these ecosystem services are difficult to measure, but available evidence demonstrates that they are substantial and growing. Many ecosystem services have been degraded as a consequence of actions taken to increase the supply of other services, such as food, which shift the costs of degradation from one group of people to another or defer costs to future generations.

The most important drivers of ecosystem change are habitat alteration, overexploitation, invasive alien species, pollution, and climate change. Evidence is growing that stresses to ecosystems are increasing the likelihood of nonlinear changes that have important consequences for human well-being. Examples of such changes include disease emergence, abrupt alterations in water quality, the creation of "dead zones" in coastal waters, the collapse of fisheries, explosions in the populations of pest organisms and other organisms, and shifts in regional climate (Millennium Ecosystem Assessment, 2005). Historically, water for the environment has been thought of as the "supplier of last resort." In developed countries, water to service municipal, industrial, and agricultural uses has been diverted from environmental uses for the most part. The specter of significant and costly environmental change serves as a warning that continued diversions from and degradations of aquatic environments will be far more costly in the future than it has been in the past.

G. The Wild Card of Climate Change

Although debate continues about the extent of human influence on climate change, there is no disagreement that the world is getting warmer and will continue to do so for at least the immediate future. Within the context of this chapter, the most relevant question to be addressed is what the effect of this change is likely to be on global and regional water resources. The only tool available for making projections into the future is climate modeling, which is an advancing but still evolving science. Climate predictions of changes in the global water regime must therefore be regarded as uncertain. Nonetheless, these models are now able to match observations of past climate behavior, and different models involving alternate hypotheses agree on a number of projections relevant to the water regime. The most significant of these are (Frederick, 1997):

- Climate change simulations predict that globally averaged surface temperature will increase from 1.4 to 5.8 °C relative to 1990 by the end of the twenty-first century.
- The timing and regional patterns of precipitation will change, and more intense precipitation days are likely.
- Models used to predict climate change suggest that a 1.5–4.5 °C rise in global mean temperature would increase global mean precipitation about 3–15%.
- Although the regional distribution is uncertain, precipitation is expected to increase in higher latitudes, particularly in winter.
- Because potential evapotranspiration (PET) increases at higher air temperature, larger PET rates may lead to reduced runoff, even in areas with increased precipitation, implying a possible reduction in renewable water supplies.
- Annual runoff is likely to increase at high latitudes, while some lower latitude basins may experience large reductions in runoff and increased water shortages.
- Flooding is likely to occur more frequently in many areas, although the amount of increase for any given climate scenario is uncertain and impacts will vary among basins. Floods may become less frequent in some areas.

- Droughts could become more frequent and severe in some areas as a result of a decrease in total rainfall, more frequent dry spells, and higher evapotranspiration.
- Seasonal disruptions might occur in the water supplies of mountainous areas if more precipitation arrives as rain rather than snow, and if the length of the snow storage season is reduced.
- Water quality problems may increase where there is less flow to dilute contaminants introduced from natural and human sources.

Agriculture and forestry are likely initially to benefit from carbon dioxide fertilization and increased water use efficiency of some plants at higher atmospheric CO_2 concentrations. The optimal climate for crops may change as temperature increases, requiring extensive regional adaptations. Hydrologic impacts could be significant in regions where much of the water supply is dependent on the amount of snow pack and the timing of the spring runoff, such as in the western United States. Increased rainfall rates could impact pollution runoff and flood control. Coastal regions could be subject to increased wind and flood damage if sea levels rise, even if tropical storms do not change in intensity.

Significant warming also could have far-reaching implications for ecosystems. Observed recent changes in climate have already had significant impacts on biodiversity and ecosystems, including causing changes in species distributions, population sizes, the timing of reproduction or migration events, and an increase in the frequency of pest and disease outbreaks. By the end of the century, climate change and its impacts may be the dominant direct driver of biodiversity loss and changes in ecosystem services globally (Millennium Ecosystem Assessment, 2005).

Global warming could well have serious adverse societal and ecological impacts by the end of this century, especially if globally averaged temperature increases approach the upper end of the modeling projections. Even in the more conservative scenarios, the models predict temperatures and sea levels that continue to increase well beyond the end of this century, suggesting that assessments that examine only the next 100 years may well underestimate the magnitude of the eventual impacts (National Research Council, 2001).

IV. DIMENSIONS OF WATER SCARCITY

The issues described in previous sections should make it abundantly clear that water scarcity will intensify in the future, and that current water consumption practices cannot be maintained without causing enormous problems. Every sector of society will have to become more efficient, and proactive measures will have to be taken to prevent further degradation of remaining supplies. In this section, the possibilities for meeting the growth in water use through conservation, improvements in productivity, economic methods, and technological developments are examined.

A. WATER SAVINGS THROUGH CONSERVATION

1. Domestic Water Savings

Total global domestic withdrawals are projected to be about 600 km^3 $year^{-1}$ by 2025, up from 344 km^3 $year^{-1}$ in 1995 (Tables II and XIII). Thus, while conservation improvements may be critically important to specific metropolitan areas and particularly those that currently rely on groundwater overdrafting, the totality of domestic conservation cannot be of major significance on a global scale. Thus, for example, the world's water reuse capacity is expected to rise by 12.6 km^3 $year^{-1}$ between 2005 and 2015 (GWI, 2005), which is insignificant compared to the projected global water need for all purposes. However, reuse will have a significant impact locally. According to Rosegrant *et al.* (2002), urban households connected to water sources used an average of 43.4 m^3 $year^{-1}$ per person, compared to 24.8 m^3 $year^{-1}$ for unconnected urban dwellers. Thus, household water demand for a city of 10 million would be 0.25–0.43 km^3 $year^{-1}$, and the projected 12.6 km^3 $year^{-1}$ increase in water reuse could meet the needs of about 300 million urban dwellers. It should be noted that reuse is currently quite expensive and widespread adoption of reuse technology would result in increases in water prices. Such increases could lead to further reductions in use as consumers seek to economize in the face of higher prices.

Educational programs, strengthened water codes, retrofitted plumbing, and installation of dual water supply systems could all have a significant influence in reducing the per capita levels of domestic consumption. Similarly, changes in home landscaping approaches in many developed countries might save up to 50% of annual household use. In short, there are significant opportunities to conserve on domestic water in urban areas. The totality of such conservation in the future may make a significant difference in local and regional water supply conditions, but is unlikely to be significant in terms of overall global water use.

2. Industrial Water Savings

Global industrial withdrawals are projected to be over 1000 km^3 $year^{-1}$ by 2025, up from 752 km^3 $year^{-1}$ in 1995 (Tables II and XIII). Of the total for 2025, only 170 km^3 $year^{-1}$ will be consumed in industrial processes.

The difference between these two numbers represents industrial waste water that is returned to the input stream. Should this water be in a polluted state, it will not only be lost, but will further degrade the source water as well. As developing countries industrialize, they face substantial water losses, should they not require industrial reclamation prior to discharge. At the present time, only developed Western countries have regulations governing industrial water use and disposal. In many instances, strict discharge regulations have provided incentives for industries to recycle. The possibilities for recycling together with the relatively high value of water in industrial uses suggest that world water supplies would be fully adequate to meet the growth in industrial demands over the coming decades.

3. Reducing Storage Losses

The volume of water lost in reservoir storage is substantial, totaling some 188 km^3 $year^{-1}$ in 1995. Improvements in the efficiency of water storage could reduce this number in the future either by using underground storage or by utilizing surface storage in areas with less evaporation. For example, Lake Nasser loses about 16% of its volume to evaporation each year (FAO, 1997), resulting in a reduction of some 10 km^3 $year^{-1}$ in annual flow, or about 20% of Egypt's annual use (Shaltout and El Housry, 1996). Storing an equivalent amount of water in the Ethiopian Highlands rather than in the lower desert portion of the Nile would reduce this loss to about 3% of the storage volume, liberating substantial quantities of additional water (FAO, 1997). Such a strategy would only be possible through basin-wide agreements for water and hydropower sharing. As in the case of domestic and industrial conservation, water savings would be local or regional and of insufficient volume to substantially reduce the global deficit created by population increase.

B. Expansion and Improvement of Irrigation

Irrigated agriculture is the dominant consumptive user of water. Thus, increases in the productivity of irrigation water through changes in management and improvements in efficiency offer the greatest potential for global water savings. Regardless of how much more efficient current use becomes, however, it seems unlikely that the increased demand for food resulting from population growth can be met without some expansion in irrigated acreage. There is both potential for future expansion of irrigated agriculture and opportunities for improvement in existing agricultural water use practices. To some extent, the expansion of irrigated acreage may depend on savings which can be achieved in current and forecasted agricultural water use. It is important to recognize, however, that improvements in agricultural water use efficiency may not yield water that would otherwise be lost because drainage water or conveyance losses by upstream users may contribute to the water budget of downstream users. Thus, it is important for the implications of changes in irrigation efficiency to be analyzed and addressed locally and regionally.

1. Potential for Expansion

Constraints to the expansion of irrigation are of three types: insufficient land, insufficient water, or excessive cost. The combination of these factors appears to explain the slower rates of expansion of irrigated lands that have prevailed throughout the last half century. Figure 9 shows the average growth rate of irrigated land globally since 1800. The expansion between 2000 and 2003 has been less than 0.3%, in contrast to the rapid growth from 1950 to 1990 following the Green Revolution. This trend, if it continues, will limit the contribution that expanded irrigated land can make to supplying the needs of the additional population in the next 50 years.

There is a great deal of land on the planet not under cultivation that is potentially suitable for irrigated agriculture. However, conversion of much of this additional land may be seriously constrained by both environmental and financial costs. Extensive development of additional irrigated land worldwide would entail the destruction of many valuable natural ecosystems. Balancing the benefits of irrigation development against the losses of ecosystem services will have to be arrived at locally or regionally.

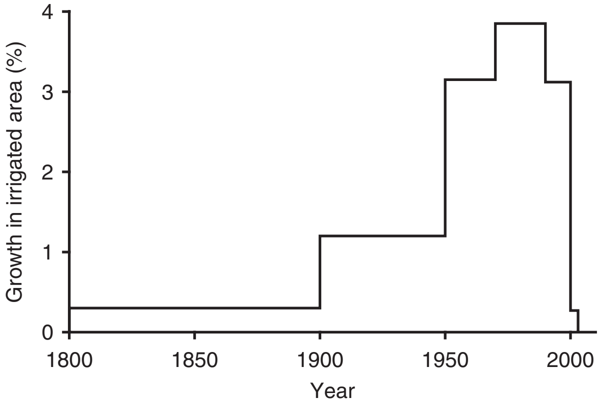

Figure 9 Rate of growth of irrigated area over the last 200 years (data from FAOSTAT).

Increasing financial costs are another constraint on expansion of irrigated acreage. Most of the desirable locations for irrigation have already been developed. The remaining sites are more remote from markets and water supplies, may not be as fertile, and may be significantly more costly to develop. Financial costs may be a critical factor limiting expansion of irrigation in the developing world where financial resources themselves are sharply constrained. For these reasons, estimates of how much new land might be brought under irrigation vary considerably.

Shiklomanov (2000) estimates that irrigation water withdrawals will expand by 685 km^3 year^{-1} from 1995 to 2025 (Table XI), to a total of 3189 km^3 year^{-1}. This 685 km^3 year^{-1} reduces the water requirement to produce food for the new population from 2740 to 2055 km^3 year^{-1}. Similarly, Rockstrom *et al.* (2007) assume that irrigation can increase by 790 km^3 year^{-1} between 2002 and 2030. Given the constraints to expansion of irrigation, it is unlikely that new development will exceed these estimates.

2. Efficiency Improvements

Care must be taken in assessing the extent to which improvements in irrigation efficiency will result in true water savings. The overall efficiency of irrigation water use is often defined as the amount of useful crop transpiration relative to the amount of water withdrawn from the source point (i.e., the stream or aquifer). By this criterion, losses during conveyance as well as the extent of subsurface drainage after application count as inefficiencies that could be reduced through technology or better management. By all accounts, current irrigation use is very inefficient by this definition. However, the extent to which the improvement of irrigation efficiency leads to water saving is complicated by the fact that drainage waters and deep percolation are often available for subsequent use. Savings in water that is available for reuse are not true savings. Thus, it will be important to assess regionally the extent to which improvements in water use efficiency locally lead to true water savings in a basin-wide context. In short, the aim of efforts to improve water use efficiency should be to reduce the irrecoverable losses of water.

Seckler *et al.* (1998) estimated the average irrigation efficiency (water required for 100% yield divided by irrigation withdrawals) for 118 countries of the world in 1990 as 43%, and showed that increasing irrigation effectiveness to 70% reduces the need for development of additional water supplies for all the sectors in 2025 by roughly 50% with a total water savings of 944 km^3 year^{-1}. Table XV, which is adapted from Wood *et al.* (2001) using data from Seckler *et al.* (1998), gives the estimated irrigation withdrawals and efficiencies in 1990 by region. The true savings that are likely to be achieved are probably less than what is reported in this table simply because some of

Table XV
Irrigation Use and Efficiency by Region in 1990 (Wood *et al.*, 2001)

Region	Irrigated area (Mha)	Irrigation withdrawals (km^3 $year^{-1}$)	Irrigation efficiency (%)
North America	21.6	202	53
Latin America	16.2	163	45
Europe	16.7	103	56
Middle East/North Africa	22.6	219	60
Rest of Africa	6.1	68	48
India	45.1	484	40
China	48.0	463	39
Rest of Asia	61.3	377	32
World	243.0	2086	43

the water "saved" is water that is currently being used by others. Nevertheless, globally efficiency improvements will result in additional water supplies and there are a wide variety of ways in which they can be made.

Postel (1998) divides the ways in which efficiency improvements can be made into four categories: technical, agronomic, managerial, and institutional. Technical improvements consist of methods for applying water more uniformly and reducing evaporation or runoff losses. Precision land leveling by laser improves uniformity of water application and allows a smaller volume of water to reach all areas of the field in sufficient quantity to ensure high yield. Sprinklers can be improved in several ways, including lowering the spray to reduce air losses and reducing the kinetic energy of impact. Surge irrigation is the intermittent application of water to a furrow achieved by alternating the flow between two irrigation sets through the use of an automated valve. This allows a more uniform application of water between the upstream and downstream ends of a furrow. Drip or subsurface irrigation minimizes water loss from evaporation and can achieve high levels of uniformity. Their cost limits the types of crop they may be used on.

Poor management is a leading cause of irrigation inefficiency, particularly in developing countries (Jensen *et al.*, 1990). Improvements in irrigation scheduling and water delivery timing will reduce water losses, as well as recognizing crop sensitivity to water stress at different stages of development. Switching to demand-based irrigation, either by soil monitoring or PET estimates, helps ensure that the right amount of water is added at the proper time. Proper tillage and field preparation can help promote infiltration and reduce evaporation (Wallace and Batchelor, 1997), and on-farm recycling of drainage and tail water can produce significant savings. The efficiency of storage and water delivery from the source to the field averages about 70% globally (Bos, 1985), and can be improved by canal lining or other repair measures.

Proper crop selection can greatly improve irrigation water productivity and efficiency (Postel, 1999). Matching crops to climatic and soil conditions and the quality of water available can ensure optimum yields for a given irrigation volume. Crop sequencing can increase productivity in saline soils, and intercropping can increase transpiration relative to evaporation. Breeding new crop varieties for tolerance to drought, salinity, and water use efficiency can potentially have a huge effect on food production efficiency.

Postel (1999) lists five institutional measures for increasing irrigation water efficiency: development of water user organizations, reducing irrigation water subsidies, establishing conservation incentives, enhancing the legal framework for water marketing, fostering infrastructure for private sector dissemination of efficient technologies, and better training end extension efforts. These are discussed in a subsequent section.

3. Deficit Irrigation

As long as water is readily available and inexpensive, irrigation practice calls for applying water so as to ensure maximum yield. However, as water scarcity intensifies, it may be more economical to under-apply irrigation at various stages of crop growth, provided these stages are not critically sensitive to water stress. Such a strategy, sometimes called "regulated deficit irrigation" (RDI), can greatly increase the productivity of water (yield per water applied) provided that yields are not substantially suppressed. Appropriate use of RDI requires knowledge of the stages of crop sensitivity to water stress so that stress is applied at times when the impact on yield and crop quality is minimized.

Table XVI, taken from Zhang (2003), shows yield and water productivity values for wheat and maize grown under different water regimes in Texas and Syria. In all cases shown, reducing applications from regular irrigation levels by one-third results in small yield reductions and significant water savings. Fereres and Soriano (2006) reviewed the literature on deficit water use and concluded that there was potential for improving the water productivity of a number of field crops provided that the level of supply of water is relatively high (i.e., >60% of PET).

Fereres and Soriano (2007) showed that strategic application of water to permanent crops at stages in the life cycle where water stress was well tolerated could lead to minor reductions in yield while crop quality was protected or even augemented. RDI in permanent crops appears to be a highly effective way to manage limited water supplies during periods of drought. It also has important implications for economizing on irrigation water in both annual and permanent crops in nondrought periods.

Table XVI
Comparison of Water Productivity (PAW) of Irrigation Levels for Wheat and Maize (reproduced from Zhang, 2003)

	Wheat, Texas, United States[a]		Wheat, Syria		Maize, Texas, United States[b]	
Irrigation level	Yield (t ha^{-1})	PAW (kg m^{-3})	Yield (t ha^{-1})	PAW (kg m^{-3})	Yield (t ha^{-1})	PAW (kg m^{-3})
Full	4.76	0.64	5.79	0.93	13.95	1.42
67% of full	4.74	0.76	5.24	1.19	11.36	1.53
33% of full	3.88	0.80	5.15	0.99	6.62	1.21
Rainfed	2.19	0.61	3.27	0.93	1.36	0.43

[a] From Schneider and Howell (1996).
[b] From Howell *et al.* (1997).

C. PRODUCTIVITY IMPROVEMENTS IN RAINFED AGRICULTURE

Since irrigated agriculture produces about 40% of the world's food on only 17% of the total land under production (Fereres and Soriano, 2007), it is about 325% as productive as rainfed agriculture. This suggests that there may be considerable opportunity to increase the productivity of the latter. Indeed, many believe that the key to averting food shortages in the coming century lies in increasing the efficiency of rainfed agriculture. This makes sense for an additional reason. Much of the future growth in population will occur in poor countries relying on rainfed agriculture for part of their needs, especially in Africa where irrigation is not widespread.

There are three main ways in which rainfed agriculture may be enhanced economically. First, there are numerous water-harvesting schemes that may be employed to increase available water. Rainwater harvesting can focus on: (1) capturing water for domestic use, for example, by collection of rain falling on rooftops in cisterns; (2) replenishing green water, for example, through stone bunds on the contour line; or (3) increasing blue water available locally, for example, through small check dams that either increase recharge to the groundwater or store water in small reservoirs. Rainwater harvesting has been used successfully to increase water for domestic, agriculture, and ecosystem uses by hundreds of thousands of communities, particularly in India. It has even brought rivers back to life. However, when practiced on a large scale in upper watersheds, rainwater harvesting will reduce water available further downstream (IWMI, 2006).

The second way in which rainfed agriculture can be enhanced is by strategic supplements of irrigation water. Supplemental irrigation with about 100 mm of water, provided during crucial drought spells, can double rainfed yields of cereals from about 1 to 2 t ha^{-1}, increasing water productivity to 0.5 kg m^{-3} of water consumed. There are many technologies for supplemental irrigation that range from farm ponds to microirrigation with shallow groundwater pumped with treadle pumps (IWMI, 2006).

The third method for increasing rainfed agricultural productivity is through improved land management. Typically, a significant amount of the rainwater striking the land surface is lost through evaporation or runoff. By enhancing infiltration and water storage capacity, more of the rainwater can be converted into transpiration and hence into enhancement of crop yields. Use of terracing, contouring, and microbasins are important measures for maximizing rainfall infiltration into the soil to increase yields, especially for farmers in sub-Saharan Africa, Latin America, and South Asia. Conservation or zero tillage—where crop residue is used as mulch—is a promising technology (IWMI, 2006).

Modest amounts of supplemental fertilization in concert with strategic water additions and improved soil management can have a dramatic effect on crop yields in rainfed systems facing periodic droughts. Rockstrom *et al.* (2002) concluded that there were no agronomic or hydrologic barriers to doubling crop yields in the semiarid tropics, and called for a new strategy of integrated rainfed management that focused on alleviating water stress and maximizing transpiration through optimized use of water, fertilization, and land management improvements. Figure 10 shows crop yields of maize and sorghum in Africa under standard and supplemented conditions. The enhancements in yield through supplemental irrigation alone were comparable to those achieved solely by fertilization, but the combination of the two resulted in yields that were up to twice as large as the controls.

D. Economic Methods for Water Supplementation in Developing Countries

The costs of large-scale irrigation projects or sophisticated technologies such as conventional drip irrigation are too high for many small-scale poor farmers in developing countries. Yet it is at this scale where the greatest gains in yield and water productivity may be gained through supplemental water additions at strategic times to avoid damaging stresses to the plant. A variety of inexpensive methods have emerged recently that are helping to raise yields in developing countries where water is scarce. These are of four types: inexpensive pumps, microirrigation devices, on-farm water harvesting, and flood recession farming (Postel, 1999).

Human- or animal-powered pumps for lifting shallow groundwater to the surface have become extremely popular on small farms in developing countries. The most promising of these is the treadle pump, a low-lift, high-capacity,

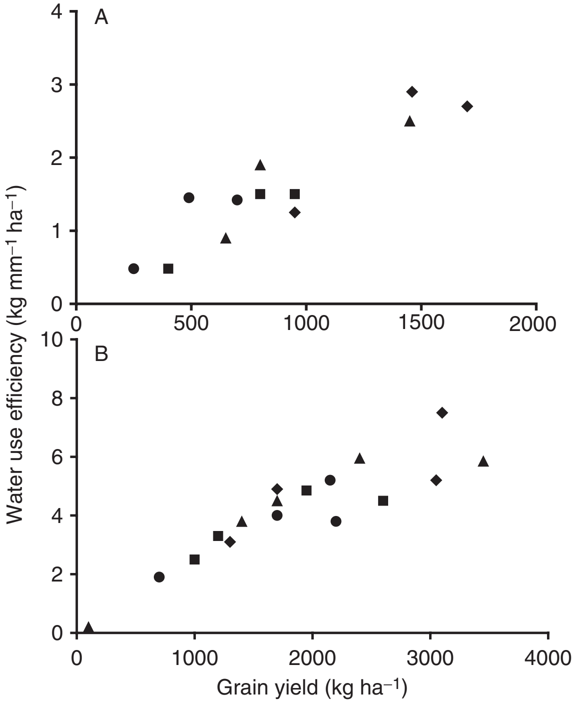

Figure 10 Water use efficiency (kg grain per unit rainfall + supplemental irrigation) for sorghum in Burkina Faso (A) and maize in Kenya (B). Control = traditional farmers' practice with no fertilizer application (circles), WH = supplemental irrigation using water harvesting (squares), FERT = fertilizer application (30 kg N ha^{-1}) (triangles), WH + FERT = supplemental irrigation combined with fertilizer application (diamonds) (after Rockstrom *et al.*, 2002).

human-powered pump designed for farms of 0.5 ha or less. It operates like a Stairmaster exercise machine, using a walking motion to provide the lift. It can fetch 5–7 m^3 of water per hour from wells and boreholes up to 7-m deep as well as from surface water sources such as lakes and rivers.

Under typical conditions, the treadle pump costs only about 25% of the retail price of motorized pumps of comparable flow rate capacity. It also costs much less to operate, having no fuel and only limited repair and maintenance costs (Perry and Dotson, 1996). As a result, farmers can recoup their investment several times over in less than 1 year. The treadle pump was introduced in Bangladesh in the 1980s, and over 1.2 million units have been sold there alone. Sales in India started later and had reached about 200,000 units by 2000, but the market potential is as high as 10 million (Shah *et al.*, 2000a).

Drip irrigation has been demonstrated to reduce water use by 30–70% and to raise crop yields by 20–90% in countries as diverse as India, Israel, Jordan, Spain, and the United States (Postel, 1999). However, conventional drip and sprinkler irrigation have capital investments that place them outside the reach of the small farmer in a developing country. Low-cost alternatives suitable for small plots or home gardens are proliferating, involving gravity feed in lieu of mechanized pressure-driven technology. The simplest of these is the bucket kit, consisting of a water-filled bucket or tank placed at shoulder height and connected to microtubes that are placed at strategic locations on the plot. Systems costing as little as US$5–10 can irrigate 100 plants (Postel, 1999). A somewhat larger version of the bucket kit is the drum kit, which uses a larger water source and can irrigate a larger area. At a larger scale are shiftable drip and stationary microtube systems, which operate like drip systems but use gravity feed and passive emission through holes or microtubes (Postel *et al.*, 2001).

On-farm water harvesting is an ancient practice now being revived to augment water supply to rainfed fields. It may consist of building embankments around the field to capture and infiltrate water during the rainy season, or more elaborate channeling to divert runoff from adjacent areas to the field. Storage tanks to collect water during the rainy season are also being revived (Postel, 1999).

Flood recession farming is the practice of growing crops on land that is flooded annually during the recession period. It has the advantage of fertility replenishment through sediment deposition, and brings more land into production. It is another ancient practice that is being revived as an alternative to dams (Postel, 1999).

E. Desalination

For many decades desalination was thought to hold promise for substantially alleviating the global problems of water scarcity by drawing on the nearly unlimited reservoirs of the world's oceans to make water readily available. Historically, the promise of seawater conversion has remained unrealized because of the relatively high costs of converting seawater to freshwater. The difficulties were compounded by the fact that desalting technologies tend to be energy intensive and there was little willingness to link the cost of water supplies to prices as volatile as those in the energy sector. There have been important advances in desalination technology in the last few decades that have brought costs down to the point where desalinated seawater may be a feasible supplement to conventional water supplies where the value of water is high. Previously, seawater conversion was utilized only in very wealthy countries that had virtually no alternative sources of supply.

The costs of seawater conversion are still relatively high so that virtually all applications are for high-valued urban uses. Thus, by the late 1990s, there were more than 12,500 desalination plants in operation in the world, generating more than 6 billion gallons of freshwater per day and accounting for about 1% of the world's daily production of drinking water (Martin-Lagardette, 2001). Inasmuch as the costs of desalination depend on a variety of factors including the degree of salinity and composition of the source water, disposal costs, and the cost of energy, not all of these systems entail the conversion of seawater.

Table XVII shows comparative costs of water for different source waters. Brackish water desalination costs are low enough that it may be economically feasible to use the process to treat saline groundwater in certain areas. There is a huge global supply of subsurface water that is currently too saline for practical use. In New Mexico, for example, 75% of the groundwater is too saline for most uses without treatment (Reynolds, 1962). It is projected that more than $70 billion will be spent worldwide over the next 20 years to design and build new desalination plants and facilities (Sandia National Laboratories, 2002).

It remains to be seen, however, whether the costs can ever be brought low enough to make desalinated water attractive for agricultural uses. High capital costs will tend to mitigate against extensive use in developing countries while high and uncertain environmental costs and the volatility of energy costs will tend to reduce its attractiveness in developed countries. Ultimately, desalination technologies may have important applications in the treatment of wastewater, though these will tend to be relatively expensive. Research on the desalinating technologies continues apace and significant research breakthroughs in the future could make desalination a more attractive source of supply than it has been in the past (National Research Council, 2004).

Table XVII

Water Costs to Consumer, Including Treatment and Delivery, for Existing Traditional Supplies and Desalinated Water (AMTA, 2001)

Supply type	Unit cost ($ per 1000 m^3)
Existing traditional supply	240–660
New desalted water:	
Brackish	400–800
Seawater	800–2100
50% traditional supply and 50% brackish water	320–730
90% traditional supply and 10% seawater	290–800

F. Improvements Through Institutional Changes

Throughout much of the world the historical means of developing water supply entailed the construction of large-scale infrastructure like dams and canals. For a number of reasons, the era dominated by the construction of large-scale water supply infrastructure is over. It is now widely understood that such facilities cause significant environmental damages and the dollar costs of those damages appears to be high (Constanza *et al.*, 1997). The relative costs of constructing and operating such infrastructure have also grown, making this approach less attractive in developed countries, and generally unaffordable in developing countries. Moreover, such projects frequently do not serve the poor, who are now a major component of the world's unserved population. The passing of the era of large infrastructure means that the greatest potential for improving global water security lies with better water management. Unfortunately, the current institutional arrangements for managing water suffer from a host of deficiencies.

Water institutions are defined as all of the collective arrangements people have made and make to facilitate the use and management of water resources. They include laws, codes, public organizations, boards, and water districts. Existing arrangements are not well adapted to modern circumstances because many institutions were created when the problems of developing and managing water resources were very different from what they are today. Water institutions tend to embody a focus on narrow interests as opposed to being holistic. They create and maintain artificial distinctions between water quantity and quality. They embody multiple and fragmented jurisdictions across river basins and watersheds, thereby making integrated resource management more difficult. Above all, there is a general absence of institutions equipped to deal with the fundamental water problem of the twenty-first century, which is scarcity (Jury and Vaux, 2005).

In some instances needed institutions are entirely absent or incompletely developed. For example, 60% of all river flows are found in transnational river basins. Yet, institutions for managing international rivers are either nonexistent or incompletely developed. There are examples of effective institutions such as the International Joint Commission which governs boundary waters between the United States and Canada and the Commission for the Protection of the Danube (International Joint Commission, 2006). And, there are a number of effective treaties. But these arrangements are the exception rather than the rule. Efficient use of water and effective management require certainty with respect to rights and ownership, and waters in international basins that are not managed to achieve these outcomes will typically not be efficiently used.

Modern water management institutions will need to incorporate two important attributes which have not received much emphasis historically. The first is stakeholder involvement. There is a growing body of evidence showing that the engagement of stakeholders specifically and the public generally is essential to the development of effective water management plans and institutions as well as the ongoing implementation of plans and policies. It is also important to recognize that stakeholder involvement should not be restricted to water plans in the developed world. On the contrary, evidence suggests that stakeholder involvement is every bit as important in the developing world as it is in the Western world (Benabdallah, 2006). The other crucial attribute needed by institutions is adaptive management, which is a systematic response to the uncertainty inherent in hydrologic and water management systems. Adaptive management embodies flexible rules and policies which permit management routines and prescriptions to be changed as more learning and experience is gained with the hydrologic system in question (National Research Council, 1999d). Increasingly, institutions which are adaptive and permit water resources to be managed adaptively are needed to accommodate hydrologic and other types of uncertainty. The fact that specific local and regional impacts of future global climate change are largely uncertain provides another compelling justification of the need for adaptive institutions.

There are several other important institutional characteristics that flow from long-standing prescriptions. For example, the European Water Framework Directive creates uniform standards for water policy within the European Union, but places the focus of management strategies on the regional or river basin level. The notion of creating uniform standards but allowing them to be applied and enforced in a decentralized way allows variations from place to place to be accounted for but ensures that the standards are of high level and that competitive environments in which they might be diminished are absent (Young and Haveman, 1985).

Inasmuch as economics is the science of managing scarcity, economic instruments such as prices and markets need to be incorporated into modern water management institutions. Water prices typically do not reflect the scarcity value of water. That is, prices generally reflect the cost of capturing and delivering water but assign a scarcity value of zero to water. This is inappropriate in an era of scarcity because it signals consumers that the water is freely available which it is not. Care must be taken, however, in utilizing prices to provide protection for poverty-stricken people who may be able to pay nothing for the water needed to support basic needs. There are numerous schemes which permit pricing to reflect the scarcity value but allow a basic or lifeline quantity of water to be available at little or no cost. Water markets are also an important institutional arrangement for managing scarcity, and market-like institutions for allocating water have begun to appear with increasing frequency in the developed world.

Research on water management institutions has lagged in recent years, which is unfortunate since much remains to be learned about human behavior in water use. For example, more needs to be known about structures of incentives, about how stakeholders should be organized, about the influence of culture on water-using behavior, and on how to devise effective programs of public education and social learning. Innovative institutions will surely be an important part of an effective solution to emerging global water problems. It will be important to update and modernize many existing institutions as well as to rely on new innovations as part of all efforts to improve water management.

V. PATHS TO SUSTAINABILITY

There is no quick fix for solving the world's water problems. Rather, improvements in water management practices are needed in virtually all of the arenas where water is used. This includes the consumptive uses that are dominant in the agricultural, industrial, and municipal sectors. It also includes practices for managing critical instream or nonconsumptive uses, particularly those related to the maintenance of aquatic and associated ecosystems. Given the expected growth in population and the large number of places where water will continue to be scarce or become so, following the path to sustainability will require a global effort at improving water use practices. All regions and locales must be part of the global effort, simply because the fundamental drivers of water supply and demand are inherently regional or local. And, this global effort must begin immediately to avoid reaching a state where the crisis will be unmanageable and the cost to the planet and its inhabitants unimaginable.

Over time, it is reasonable to assume that new scientific advances will offer potential help in adapting to the water realities of the future. In this connection, it is important to recognize that some of our existing scientific knowledge about water and its management remains underutilized or ignored. For example, it is well known that it is almost always cheaper to prevent the pollution of water courses and groundwater at the outset than it is to clean up and remediate pollution events after they have occurred. This suggests that a premium should be placed on developing and enforcing regulations that tend to make episodes of pollution the exception rather than the rule.

One important principle guiding future management paradigms should be to avoid actions that make the situation worse than it needs to be. Examples of these undesirable actions are practices that lead to water pollution, lead to environmental impairment or destruction, or encourage low-valued uses of water while higher valued uses go unserved. A corollary principle is that sustainable management practices and norms of use should be developed wherever they can. As used here, the principal of sustainability requires that the quality and quantity of water available to future generations should not be significantly impaired by the actions of current generations (Rawls, 1971; Weiss, 1989). As a general proposition, sustainable practices will usually be preferable to those that are inherently unsustainable. Some unsustainable practices will be inevitable, however. The extraction and use of fossil groundwater or other groundwaters that do not recharge is inherently unsustainable because any use hastens the day of exhaustion. In these instances, it will be important to ensure that the resource in question is used in ways that build the physical and social capital available to the society of the future. Of necessity, the concept of sustainability will be highly nuanced. Nevertheless, available science as well as common sense points to numbers of unsustainable water management and water use practices that need to be ended as a matter of priority.

A. Ending Unsustainable Practices

The first step on the path to sustainability is to implement a strategy to reverse unsustainable practices that are depleting or damaging water resources excessively. Despite the *a priori* urgency of ending unsustainable practices, it will not always be cheap or even practical to reverse them. This is particularly true in developing countries that do not have the resources and, in some instances, the know-how to implement known management practices that would be more sustainable. These difficulties will be identified in the discussion that follows. The three most significant unsustainable practices that exist worldwide are persistent groundwater overdraft, the continuing contamination and pollution of groundwater and surface waters, and inappropriate management of watersheds.

Persistent groundwater overdraft is always self-terminating, and potentially disastrous if left unmanaged. The transition to sustainability therefore requires that termination of overdraft be managed in terms that are most economically and hydrologically advantageous. It also requires that such changes in management regimes be timely to allow for the development of alternative supplies, where possible and justified, or for scaling back water use in an orderly manner where that is called for. The economic and hydrologic principles for managing groundwater are well established. What is needed is the institutional and political will to apply them in regions that are persistently overdrafting groundwater. Although opinions differ about the severity of consequences that may occur in regions where critically needed food is produced through excessive pumping, an immediate plan is needed for reducing water use to levels that can be supported by available supplies. While there may be doubts about the seriousness of overdraft or the availability of substitute sources of supply, the loss of ability to feed hundreds of millions of persons would be such a serious prospect that careful contingency plans should be devised and implemented to avoid it (Moench *et al.*, 2003).

The world is already feeding some 500 million people with food grown in regions suffering chronic overdraft (Postel, 1999), and a significant part of the projected population growth in the future will be in these same regions. Strategies for reducing persistent groundwater overdraft by agriculture may involve changes in cropping patterns, investment in new technology, repair, and upgrading of infrastructure, and even deficit irrigation. To be successful, all of these strategies must result in reduction of extractions. Where extractions are not reduced sufficiently, reductions in crop acreage may be the only alternative. In some cases, water transfers or the development of supplemental supplies may help to offset the loss of accustomed levels of groundwater use that are required to terminate persistent overdraft. In almost all instances, the development of new supplies is likely to be enormously expensive and must be considered to be a last resort.

It is important to recognize that there are circumstances in which coordinated groundwater management schemes may not be possible. In India, for example, there are some 22 million farmers independently extracting groundwater from common and interrelated aquifers. It probably would not be feasible, much less practical, to develop the institutional arrangements needed to coordinate their water-extracting behavior to achieve the desired reductions. For this reason, the Indian government is developing a massive surface water importation scheme that will cost many billions of dollars. Whether the Indian government or any other government can afford such schemes remains an open question (Shah, 2000, 2003).

Persistent groundwater overdraft by large metropolitan areas can be even more serious because reduction of water supply could have immediate life-threatening consequences for large numbers of people. In addition, groundwater overdraft can cause damaging land subsidence within a metropolitan region. In Mexico City, for example, land subsidence of 7.5 m has occurred in the downtown area since pumping began (National Research Council, 1995). Since urban demands for water will always take precedence over other priorities, water-short cities may end up drawing water from adjacent agricultural operations to satisfy their needs, or alternatively developing large water transfers. The Mexico City case is particularly alarming because there are apparently no locally available substitute supplies and the costs of lifting remote supplies to the Valley of Mexico at an elevation of 2500 m would make such water unaffordable to most of the residents of Mexico City. By contrast, the chronic water supply shortfall in Beijing, China has forced the government to divert substantial water from surrounding farmland and to initiate a water diversion from the Yangtse River in the south at enormous expense (Postel, 1999). There are many less expensive opportunities to achieve water savings in metropolitan areas. These include the repair and maintenance of infrastructure, metering water use, pricing water realistically, education, water reuse, and other conservation programs (National Research council, 1995).

The assertion that inadequate measuring and monitoring of groundwater casts doubts about the severity of overdraft does not justify inaction (Moench *et al.*, 2003). There is certainly a crucial need to develop real-time monitoring and measuring systems for aquifers around the world. However, the urgency of emerging water problems will not allow the luxury of waiting for a period sufficient to document beyond all doubt that an aquifer is being persistently overdrafted and economic exhaustion is in sight. This is particularly true where alternative sources of supply are either unavailable or largely uneconomical to develop.

Pollution of surface water and groundwater poses a threat that must be sharply reduced and eliminated where possible. Moreover, pollution problems must be solved in both developed and developing countries. In developed countries, the continuing creation of new chemicals that can ultimately be dispersed in the environment, the incompleteness of strategies for controlling nonpoint source contaminants, the emergence of new constituents of concern such as endocrine disruptors, and the continuing threat to groundwater quality from past chemical use and disposal practices will all require renewed and more intense attention. Failing that, available high-quality supplies in advanced countries will continue to diminish even as demands for those waters grow.

The water quality problem is even more serious in developing countries, where excessive pollution poses significant health threats as well as a loss of needed water supply. The absence of adequate sanitation services for over 2 billion people—most of whom live in developing countries—by itself poses an enormous threat to water quality. That threat is likely to intensify as population grows. It has the potential to condemn the populations of developing countries to an ever-tightening spiral of population growth followed by increased pollution leading to a further loss of badly needed high-quality water supplies. Examples abound. China expert Vaclav Smil has estimated that as much as 20% of China's river water is too polluted for even irrigation purposes (Postel, 1999). The aquifer on which Mexico City depends for 75% of its water supply is potentially vulnerable to pollution from a variety of pathogens and toxic chemicals (National Research Council, 1995).

Economic development in many of these countries will be difficult to initiate and sustain. As industrialization and more intense agriculture develop, there will be an understandable reluctance to restrain such development through the imposition of effective anti-pollution measures. Additionally, the expense of undertaking more centralized government-sponsored pollution clean-up programs may be greater than can be supported in a developing economy. It is also true that in the absence of effective regulation, industry and agriculture in developing economies will be likely to emit contaminants that have long been controlled or banned in more developed nations.

Many developing countries are likely to have to rely on external technical and financial aid if they are to address successfully the pollution problems that are likely to be associated with economic growth. The enormous costs of remediation and clean up of groundwater and surface water supplies suggest that, from a broad perspective, it would likely be cheaper to take whatever actions are needed to avoid severe pollution episodes. But from the internal perspective of a developing country, it may not look this way at all. This suggests, then, that global and regional programs of financial aid to protect and enhance water quality may need to be underwritten by the developed world.

The potential for salinization of lands where irrigated agriculture is practiced is another particularly insidious threat to water quality. Virtually all irrigation water contains salts which are left behind in the root zone of the soil profile as the water is evaporated from the soil surface and transpired by plants. As salts build up they restrict plants from extracting water from the soil and ultimately the land ceases to be productive. The threat of this process is present wherever irrigated agriculture is practiced and is more serious the larger the salinity concentration of the water. The scientific principles of managing salinity are well known and are competently practiced in some areas of the world (Knapp, 1991). Ironically, the best way of managing salinity requires more water to leach salts from the soil and drainage facilities to carry the leachate off into a suitable disposal site. Agricultural salinity is insidious both because it can destroy the productivity of agricultural land and because controlling it requires additional supplies of water that are already scarce in most regions of the world.

Up to 47.7 million ha of irrigated land worldwide (about 21% of the total) has been degraded by salinity, with many millions more likely to be degraded in the next decades in the absence of management changes (Postel, 1999). In the coming decades when there will be a need to increase global agricultural productivity substantially, every effort will have to be made to attenuate or stop the destruction of agricultural lands through salinity. Failure to deal with this problem effectively will greatly increase the difficulties of meeting future food demands and managing scarce water resources.

Salinization is not the only water-driven process affecting land that must be addressed to achieve sustainability. Inappropriate land management practices on upland watersheds can lead to the degradation of water quality and increase runoff volume and variability over time (National Research Council, 1999b). Integrated water management strategies have worked well in some instances in addressing the problems of protection and appropriate land use in watersheds. Much remains to be done in the developed world, however, where the problems of watershed management are formidable. Frequently, the residents of upland watersheds are poverty stricken and must use all of their meager resources to wring a living from the land. The pressures of mere survival often preclude any efforts to manage and husband watershed lands in a sustainable way (Benabdallah, 2006; Sullivan, 2006).

There are many other nonsustainable practices beyond those discussed which are site specific and restricted to particular regions and locales. It will nonetheless be important to modify such practices where feasible so that they are sustainable.

B. Management Strategies

There is much that can be done by way of improvement of water management strategies around the world. Management strategies include those that are technically based such as integrated resource management, conjunctive management of groundwater and surface waters, underground storage, and irrigation scheduling, and institutional strategies which include a panoply of economic, political, and other instruments designed to change behavioral approaches to water management. While it is unlikely that all water management strategies can be used everywhere, it is clearly possible to devise a mix of strategies that will be appropriate for each region and locale. Again, the involvement of stakeholders in the development and implementation of management strategies will be crucial to achieving success.

Technically based management strategies rely for their effectiveness on scientific knowledge about the behavior of water and the effectiveness of various ways of managing it. Integrated resource management refers to a strategy that manages water and associated land and air resources as an integrated whole. The concept acknowledges that management actions focused on one resource have implications which are frequently very significant for other resources. In addition, integrated management embodies the notion that the watershed should be the fundamental unit of management because it is the fundamental hydrologic unit. Typically, the management of watersheds is confounded by the fact that different political jurisdictions overlay a single watershed. These jurisdictions can be anything from nations to provinces or states, to overlapping local units of government. The job of managing hydrologic resources on a unified basis as well as the practice of integrated resource management is made enormously difficult by the absence of a single jurisdictional entity. The usual result is that watersheds are not managed in a unified way and integrated resource management is rarely, if ever, practiced (Naiman, 1992; National Research Council, 1999b).

Experience indicates that efforts to move toward strategies of integrated resource management, including watershed management, must proceed in a stepwise fashion. In general, experience shows that such efforts are more likely to be successful on smaller watersheds. The larger the watershed, the more complications, so that experience with smaller units can be very important when devising management strategies for large basins. Additionally, there is no one prescription for integrated resource management. Each watershed is different both physically and sociologically, and management efforts must be adaptive. That is, the strategy should be flexible to begin with and should be adjusted or adapted periodically to reflect the results of experience with time. Again, efforts at integrated resource management are more likely to be successful where stakeholders are involved and the public is engaged (Doppelt *et al.*, 1993; National Research Council, 1999b).

Although resource management is typically more difficult to practice in an integrated fashion in very large river basins, there is still a critical need for formal basic allocation mechanisms (McCafferty, 1998). Most of the surface waters and nearly all of the groundwaters of the planet that transcend international boundaries are not subject to treaties or formal decrees or doctrines specifying the rules of allocation. This means that in most cases, entitlements are clouded or uncertain. A lack of certainty about water entitlements constrains the development and sometimes the use of water resources. People are often understandably reluctant to rely on water supplies whose legal allocation is clouded. A high priority in every transnational watershed on the globe should be to establish clear treaties or allocations which firm up legally the respective rights to use water and apportion various quantities of groundwater and surface water flows. This will not be an easy undertaking, yet it will be essential. The longer the wait the higher the stakes in any effort to allocate and the higher the stakes the more difficult it will be to forge multilateral agreements.

Conjunctive use of groundwater and surface water acknowledges that there are inherent hydrological interconnections between these apparently different sources of supply. At its simplest, conjunctive use entails the reliance on surface waters during times of average or above average precipitation and runoff. During drought periods or other times when surface water availability is constrained, use shifts to groundwater which tends to be buffered to some extent from the variabilities that surface water is subject to. Looked at differently, groundwater can be managed as a reservoir for use during periods of surface water shortfall and recharged during periods of normal or above normal availability of surface water. Sophisticated schemes of conjunctive use employ managed recharge whereby excess surface waters are captured and transformed into groundwater. Managed recharge can be accomplished simply through the use of surface spreading or through direct injection, which generally requires significant investment in facilities.

There are several preconditions for effective conjunctive use. First, the management strategy must be structured to acknowledge the holistic nature of groundwater and surface waters. Second, there must be clear systems of water rights for both groundwater and surface water. Too often, groundwater rights are poorly defined or absent. This latter circumstance tends to lead to underinvestment in conjunctive use or no investment at all. The scientific principles of conjunctive use have been well understood for decades, but there has been a lack of will and resources to apply them widely (Morel-Seytoux, 1985). Conjunctive use is one of the strategies that will need to be employed on a widespread basis as part of the response to emerging water problems. Conjunctive use and managed recharge are one means of addressing persistent groundwater overdraft.

Strategic utilization of underground storage is related to conjunctive use. The construction of surface water storage facilities to capture water in wet times and places and hold it for use in dry times or convey it to dry places has been a time-honored method of dealing with hydrologic variability and related water scarcity. The easily accessible and economically attractive surface water storage sites have already been developed. With a few exceptions, those that remain are either very expensive to develop or in remote locations. In addition, surface water storage facilities are now known to cause significant damages to riparian ecosystems. In contrast, underground storage offers the potential for sequestering large quantities of water while avoiding environmental and economic problems that tend to be associated with surface storage facilities.

Underground storage is likely to be more costly than simple conjunctive use schemes, however. Investment is required in recharge facilities, even where simple land spreading is used. Care must be taken to ensure that recharge waters are of appropriate quality (National Research Council, 1994). There are a number of technical problems such as clogging that must be managed. Underground storage offers significant opportunities worldwide to alleviate water scarcity, but the costs may be beyond the capacity of many developing nations to finance. External financial aid and technical assistance will likely be required if the full potential of underground storage is to be realized, particularly in the developing world.

There are, of course, many ways in which water-scarce countries may adapt to an associated scarcity of food some of which are explored by Moench *et al.* (2003). One important example concerns the concept of virtual water. Currently, there are countries that do not have sufficient indigenous water supplies to feed existing populations. In the next 15–20 years many more countries will join this list, including India and possibly China (Yang *et al.*, 2003). There is evidence to suggest that when countries become unable to grow sufficient food to feed their populations, they respond by importing cereal grains and other agricultural commodities. One way of viewing these imports of agricultural commodities is based on the proposition that the importation has the same impact as developing locally the water needed to grow the commodities. In another words, agricultural commodities carry with them embodied water or the water that is needed to grow them. Importing countries then, in effect, import water by importing crops. Such water is sometimes called "virtual water" (Yang and Zehnder, 2002). This route offers one potentially significant adaptation via international trade through which water-poor countries can import water-intensive agricultural commodities from countries that are more generously endowed with water resources. There are several constraints and implications of this method of adaptation which need to be noted.

The extent to which countries can adapt to water scarcity by importing foodstuffs will, of course, be partly a function of their ability to generate foreign exchange. This may be problematic for the poorest of countries, particularly those in Africa. In the absence of adequate foreign exchange, world food relief organizations may be able to assist but there has been no systematic assessment of the potential for such organizations to respond to a world food crisis. Thus, it is unclear to what extent water-scarce countries can offset that scarcity by importing food and to what extent international trade can ameliorate water scarcity globally.

There is in addition another crucial fact that emerges from analyses of the prospects of virtual water. If water scarcity manifests itself rather directly as food scarcity, the demand for food exports from countries that have relatively generous endowments of water should expand. (These countries are found in Europe and the Americas.) To the extent that food for export is grown in irrigated agriculture the derived demand for water in those countries will also expand. Through this mechanism the water scarcity of water-short countries worldwide will have direct impacts on the demand and availability of water in the water-rich countries. For this reason alone, it will be important for water-rich countries to stop unsustainable water management practices, adopt improved management strategies, and, in general, practice water stewardship more carefully than has been the case in the past (Vaux, 2004).

All of these general management strategies as well as those that are specially adapted to particular regional and local circumstances will have to be devised and implemented in an environment that is cloaked with uncertainty because of global environmental change. While knowledge of the likely impacts of global warming grows significantly with time, it is still not possible to predict the specific effects that will occur on a regional basis. What is known is that change is likely, and weather extremes will become more common (Section III.G). The fact that the world will have to adapt to water scarcity in the face of this added source of uncertainty makes the task of global water management more difficult. It will place a premium on the capacity to devise strategies that are adaptable and can be adjusted as climate changes. For that reason, the focus should be on the delivery of services and not on the development of infrastructure. Adaptive management will be critical and large-scale infrastructure is typically difficult to manage adaptively. Moreover, it is likely to be easier to respond to climate change if water resources are well managed to begin with. This means that unsustainable practices need to be corrected and management strategies should be as adaptive and flexible as possible (Vaux, 1991).

C. Agriculture and Water Management in the Developing World

Agriculture will continue to be the dominant consumptive user of water globally. As population and the demand for food grow, it will be important to find ways to increase the productivity of agriculture everywhere. Irrigated agriculture is far more productive than rainfed agriculture, and there are many ways in which the productivity of irrigated agriculture can be increased in developed countries (Section IV.B). The poorest regions of the planet are likely to be the ones hurt worst by a water crisis in the future. But many of these same regions have the greatest potential for increasing crop yields from currently low levels. Modest investments or subsidies in the soft-path technologies can produce dramatic increases in productivity at the local level not just with irrigated agriculture but with rainfed agriculture as well (Section IV.C). Improvements in the water use efficiency of rainfed agriculture need to be developed and disseminated through training programs. Thus, for example, simple water harvesting techniques, improved crop rotations, and other relatively inexpensive and decentralized techniques and technologies can have a disproportionate impact on the productivity of rainfed agriculture worldwide. While past water management practices have focused on the development and utilization of surface water and groundwater, future practices will have to focus relatively more on the utilization of rainfall through improvements in rainfed agriculture.

Just as soft-path, decentralized, and inexpensive technology will be the key to improving agricultural productivity in the developing world, the same sorts of technology will have to be created to provide drinking water and sanitation services to the underserved poor in developing countries. The evidence suggests that it will be critically important to have low-cost, community-managed water supply and sanitation services. Infrastructure alone often does not lead to an increase in access to water and sanitation services because top-down technology-driven projects frequently do not involve the users directly, tend to be poorly maintained, are subject to breakdown, and have short usage times. In addition, low levels of financial recovery in poor countries mean that operating and maintenance costs are not covered, so the systems do not function as intended and are badly managed (Rijsberman, 2004).

The Millenium Development Goals, established in 2000, call for a halving of the number of people who do not have adequate access to water and sanitation services by the year 2015. Although few expect those goals to be achieved, progress is being made. The UN Development Programme made an early analysis and noted that a group of countries containing 40% of the world's population, primarily in Asia, have either achieved the goals or are on track to achieving them. China and India containing roughly half the world's unserved population are among this group and their high rates of economic growth suggest that the prospects for achieving the goals are good (Rijsberman, 2004; United Nations Development Programme, 2003). A second group of countries containing 30% of the world's population, primarily in Africa, are not making progress (United Nations Task Force on Water and Sanitation, 2003). The results of this analysis suggest that external funding should be focused on Africa and a few other countries that appear not to be making progress.

The important point here is that the Millenium Development Goals have focused attention on the problem of drinking water and access to sanitation services and significant progress is being made toward worldwide provision of these services although the Millennium Goals are unlikely to be met in the proposed time frame. There are no similar programs focusing on the use of water in agriculture and the production of food to feed a more populous world, however. A clear conclusion is that although provision of adequate water supply and sanitation services is deserving of the highest priority, finding and implementing ways to improve the productivity of water in agriculture, particularly rainfed agriculture in developing countries, is not far behind.

D. Societal Changes

There are a number of collective actions that can be taken by the global population that can also make a difference. Such actions will require individuals to make choices that will benefit the larger population as a whole. Such choices will, at times, run counter to personal preferences. Thus, such collective action will probably require a new global water ethic or some other system of incentives if collective action is to be effective. There are several examples of important collective actions that could be taken and they include changes in dietary patterns, a conservation ethic, and cooperative management of shared resources.

Selection of appropriate dietary patterns can have an enormous positive effect on the global water balance. Evidence shows that as countries develop economically diets change and become much richer in meats. Yet, meat consumption entails approximately eight times the water input per food calorie produced compared to a vegetarian diet (Falkenmark and Rockstrom, 2004).

A simple example illustrates the impact. A person for whom meat accounts for 10% of the daily caloric intake will require 1.7 times more water input to produce that food than a person whose diet contains no meat. Of course, to the extent that the water input comes from rainfed circumstances the impact may not be as great. Nevertheless, dietary shifts on a global basis can be quite important. Even shifts from beef to pork or chicken will result in substantial water savings (Smil, 2000). It seems unlikely that populations in developing countries would be willing to forego meat in their diets without some concomitant changes in developed countries.

Another example of collective action would be a global water conservation ethic. In developed countries, levels of personal and household water use are usually much higher than those in developing countries (National Research Council, 1999a). Some of that use is either low valued or outright waste. Thus, one strategy for stretching water supplies during drought periods entails appeals and other incentives to use water more carefully in everyday uses such as landscape irrigation and interior household uses. The typical pattern is that when such appeals are effective, water use returns to pre-drought levels once the drought is over. There is little question but that much water could be saved with a resulting amelioration of world water scarcity if the kind of water conservation practices that are typical of drought circumstances in developed countries were practiced on a consistent basis. This would might, in turn, provide an example for developing countries.

A final example of collective action would be the widespread adoption of collaborative arrangements for governing and allocating shared water resources. There is a strong tendency to treat such resources in a competitive fashion. When property rights to water are treated in this way, it is frequently true that low-valued uses in one sector are served while higher valued uses in other sectors go begging. This means that the aggregate productivity of water is less than it might otherwise be. Collaborative arrangements in which there is a commitment to allocating water to its most productive and highest valued uses and a parallel commitment to flexibility and adaptability in allocation would help to ensure that water is used as productively as possible. Use opportunities change over time and in a world of water scarcity it makes little sense to continue to allocate water to existing, relatively low-valued uses, as new higher valued uses are emerging.

We are not optimistic about the prospects for development of worldwide collective action to conserve and economize on water. There are few, if any, examples of such collective action, and the worldwide approach to global warming illustrates how difficult the development of such collective action can be. Nevertheless, such collective action could make a big difference in addressing the emerging world water scarcity and we would be remiss in failing to mention it.

VI. CONCLUSIONS

In this chapter we have sought to portray an emerging world water crisis and to identify the global responses that will likely be effective in addressing it. It is clear that the need to provide water and sanitation services to a large portion of the world's population and the need to feed a sharply larger population, most of it in the developing world, will place unprecedented strains on the world's water resources. There is much that can be done in response to manage water in a sustainable fashion. There are many modern management strategies that are not yet employed on an extensive basis. New and emerging technologies and scientific findings will help as well improvements in governing and managing institutions. The problems are daunting but we are not without means to address them.

It is important to recognize, however, that water is just one of the challenges that will have to be addressed as the twenty-first century progresses. As population grows and economic development proceeds there will be threats and crises in many sectors that sustain life and are important to the quality of life. Demands for energy and materials will grow, as will the problems of disposing of their residuals. There will be enormous pressures for provision of housing and education, for food and nutrition, and in protecting and preserving planetary life support systems (National Research Council, 1999c). All these loom as compelling problems that will have to be solved. Thus, water is but one resource and poses but one of many sets of problems that will have to be addressed and managed if a sustainable world with a much larger population is to be created. Just as water is woven through many of the other challenges such as the provision of adequate food and nutrition and the preservation of life support systems, those challenges and how we address them will also have important implications for our success in addressing the emerging water scarcity of the twenty-first century.

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